

Print ISSN : 2395-1990

Online ISSN : 2394-4099

<https://ijsrset.com>



**CONFERENCE
PROCEEDINGS**

SPECIAL ISSUE

**NATIONAL CONFERENCE ON
RECENT ADVANCEMENTS AND EMERGING
TECHNOLOGIES IN MECHANICAL ENGINEERING
(N CRAETME-2026)**

Date : 18 March 2026



Organised by

Department of Mechanical Engineering, FoET

Dr. Shakuntala Misra National Rehabilitation University,

Lucknow 226017 – Uttar Pradesh (India)

**INTERNATIONAL JOURNAL OF SCIENTIFIC
RESEARCH IN SCIENCE,
ENGINEERING AND TECHNOLOGY
VOLUME 13, ISSUE 6, MARCH-APRIL-2026**

Email : editor@ijsrset.com Website : <http://ijsrset.com>



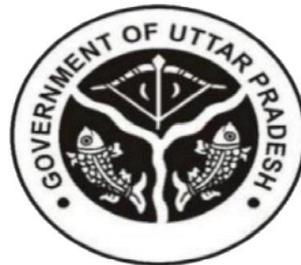
**National Conference on Recent Advancements and Emerging
Technologies in Mechanical Engineering**

[NCRAETME-2026]

On

18th March 2026

Organized by



**Department of Mechanical Engineering, FoET
Dr. Shakuntala Misra National Rehabilitation University,
Lucknow 226017 – Uttar Pradesh (India)**

In Association With



**International Journal of Scientific Research in Science,
Engineering and Technology**

Print ISSN : 2395-1990 Online ISSN : 2394-4099

Special Issue : Volume 13, Issue 6, March-April-2026

Published By





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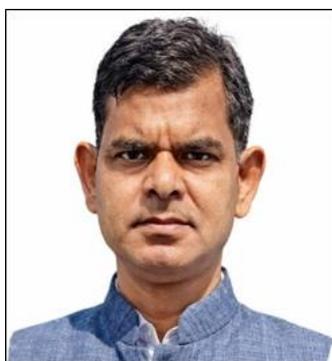
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ABOUT CONFERENCE

The National Conference on Recent Advancements and Emerging Technologies In Mechanical Engineering (NCRAETME-2026) is being organized by the Department of Mechanical Engineering at DSMNRU, Lucknow. The conference provides a platform for researchers, academicians, industry professionals, and students to present innovative research and exchange ideas on emerging trends.

CONFERENCE OBJECTIVES

1. Facilitating the exchange of research findings, innovative ideas, and best practices among researchers, engineers, and students.
2. Connecting professionals to foster partnerships between academia, industry, and government to address complex, interdisciplinary challenges.
3. Providing platforms for researchers to present their work, receive feedback, and publish findings in reputed journals or proceedings.
4. Promoting sustainable, resilient, and inclusive solutions that align with goals like the UN SDGs.
5. Providing opportunities for students and early-career engineers to interact with experts and showcase their research.

ABOUT THE UNIVERSITY



Dr. Shakuntala Misra National Rehabilitation University, established by Government of Uttar Pradesh in the year 2008, is a highly innovative that proactively brings together under one umbrella-the academia and social responsibility. The potent synergies of this blending open up huge possibilities for translating ideas into action, taking science to soil, and lab to land. First of its kind in India, the University not only offers accessible and world class higher education to all but also addresses the educational needs of the physically challenged in a seamless and sensitive academic environment.

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The University encourages inter-disciplinary and multi-disciplinary approach for holistic academic development of faculty and students alike. Dedicated and distinguished faculty with wide exposure in their respective disciplines make for lively transaction of knowledge and vibrant class room atmosphere. The course curricula of various courses in the

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There is an on-going endeavor to expand University-Industry Interface and upgrade in-house capabilities to conduct professional and job-oriented courses that are compatible with the emerging trends of economy and employment-markets. Integration of students into global socio-economic mainstream is at the top of the University agenda. The University is geared to prepare the students for life of dignity through effective delivery of educational services, integrated and inclusive approach in imparting life skills to the students, institutional and human resource interventions, building proactive and meaningful academic partnerships to provide high quality, relevant, and responsive learning environment for one and all.

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Natural Fiber Hybrid Composites: A Comprehensive Review of Materials, Properties, and Applications

Aman Singh^a, Dipak Kumar^b

^a 3rd YEAR , Mechanical Engg. Department, Govt. Polytechnic , Gorakhpur, Uttar Pradesh, India

^b Lecturer, Mechanical Engg. Department, Govt. Polytechnic , Gorakhpur, Uttar Pradesh, India

ARTICLE INFO

Article History:

Published: 18 March 2026

Publication Issue :

Volume 13, Issue 7
March-April-2026

Page Number :

01-07

ABSTRACT

Natural fiber reinforced hybrid composites have gained popularity recently due to its affordability, low weight, biodegradability, and environmental friendliness. To increase strength and toughness, these materials combine natural fibers with artificial ones like carbon and glass. This paper examines the interactions between several natural fibers and synthetic fibers in polymer-based composites, including flax, sisal, kenaf, jute, and banana. The performance of these hybrid materials is greatly influenced by crucial elements such as the fibers' treatment, layering, orientation, and ratio of natural to synthetic fibers. Tensile strength, flexural strength, interlaminar shear strength, and fracture toughness can all be increased by employing both natural and synthetic fibers, according to the study. The review also covers the benefits, drawbacks, and possible uses of natural fiber hybrid composites in the packaging, automotive, aerospace, and structural sectors. According to the results, hybrid composites can partially replace composites reinforced with synthetic fibers while preserving favorable mechanical qualities and lessening their negative effects on the environment.

Keywords: Natural fibers, Hybrid composites, Mechanical properties, Interlaminar shear strength.

INTRODUCTION

In order to gain improved mechanical and physical qualities, two or more separate components are combined to create composite materials. A matrix phase and a reinforcing phase, such as fibers or particles, typically make up composites. The matrix shields the fibers from environmental deterioration while binding the reinforcing materials and distributing loads among them .High strength, stiffness, and durability are characteristics of synthetic fiber reinforced composites like carbon fiber reinforced polymers (CFRP) and glass fiber reinforced

polymers (GFRP). Nevertheless, these materials have a number of drawbacks, such as being expensive, not biodegradable, and posing environmental risks when disposed of these material.

Natural fibers have been investigated as substitute reinforcement materials to address these issues. Natural fibers with low density, renewability, biodegradability, and availability include flax, sisal, kenaf, jute, and banana. However, as compared to synthetic fibers, natural fibers by themselves frequently show greater moisture absorption and lesser mechanical strength. In order to balance mechanical performance and environmental sustainability, hybrid composites blend synthetic and natural fibers within a polymer matrix. Compared to traditional composites, these materials offer better mechanical strength, less weight, and cheaper cost. Fig.1 shows classification of plant fiber composites.

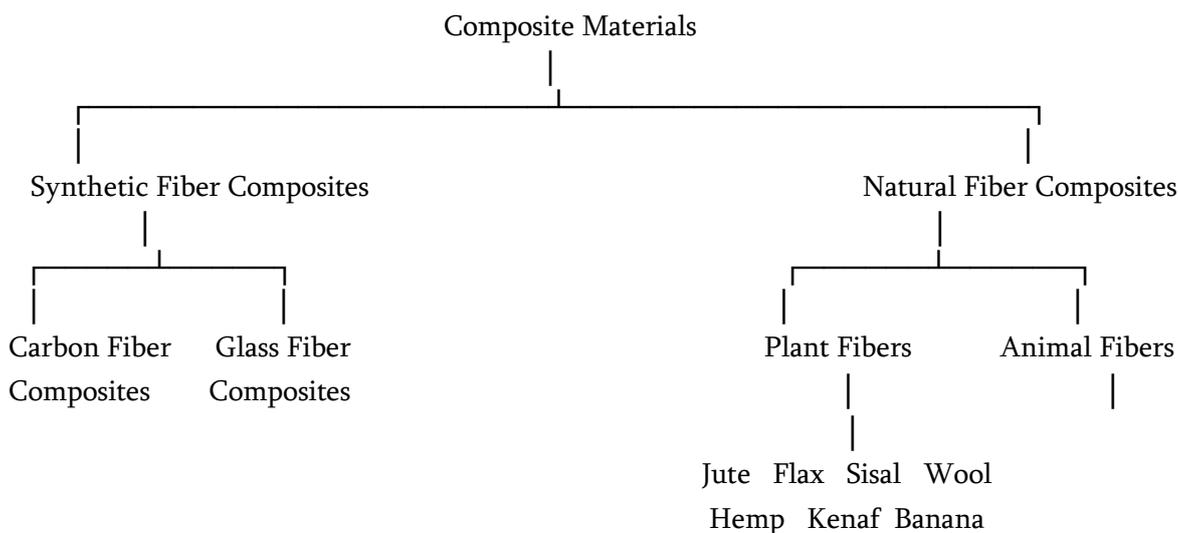


Fig.1 Classification of plant fiber composites

Literature Review :

The sustainability, biodegradability, and lightweight properties of natural fiber reinforced polymer composites have drawn a lot of interest. Nevertheless, single natural fibers frequently have drawbacks such poor heat stability, high moisture absorption, and reduced mechanical strength. Researchers have concentrated on hybrid natural fiber composites, which blend two or more fibers to improve composite performance, as a solution to these problems.

In their thorough analysis of natural, synthetic, and hybrid fiber reinforced polymer composites, Jomboh et al. [1] emphasized that hybridization enhances the mechanical and thermal characteristics of polymer composites while preserving environmental sustainability. According to the scientists, these composites are appropriate for engineering applications because they improve stiffness, tensile strength, and durability when natural fibers are combined with other natural or synthetic fibers.

In a similar vein, Mohammed et al. [2] examined the development of sustainable natural fiber hybrid composites and highlighted how hybridization techniques greatly enhance the mechanical, physical, and thermal properties of composite materials. In order to increase the interfacial bonding between the fiber and matrix, their study also included the significance of fiber surface treatment and appropriate fiber selection. Nagaraja et al. [3] conducted a thorough analysis of current advancements in environmentally friendly natural

fiber composites. The authors came to the conclusion that because of their enhanced mechanical performance and reduced environmental effect, hybrid natural fiber composites are viable substitutes for synthetic composites. The study also emphasized how crucial fabrication methods, fiber orientation, and fiber volume percent are in shaping the final composite material qualities.

Significant increases in mechanical characteristics through hybridization have also been shown in recent experimental experiments. Saba et al. [4] found improved mechanical performance and dimensional stability in hybrid epoxy composites reinforced with *Washingtonia* and kenaf fibers. They discovered that hybrid reinforcement produced better tensile and flexural capabilities by enhancing load transmission between fibers and matrix.

Kaufmann et al. [5], who examined processing methods, material characteristics, and new uses for natural fiber hybrid composites, reported more developments. Their research highlighted how manufacturing techniques including resin transfer molding, compression molding, and manual lay-up have a big impact on the performance and quality of hybrid composites. The authors also mentioned that because these materials are lightweight and eco-friendly, the automobile and aerospace industries are using them more and more.

Kumar et al. [6] investigated epoxy-based hybrid composites reinforced with coir, pineapple leaf, and jute fibers in a different experimental study. The findings showed that hybrid fiber reinforcement greatly increased thermal stability, flexural strength, and tensile strength. Additionally, the study used machine learning algorithms to forecast the mechanical characteristics of hybrid composites, demonstrating a great deal of promise for improving composite design.

In a similar vein, Raj et al. [7] investigated the mechanical properties of hybrid polymer composites based on natural fibers and discovered that appropriate fiber combinations and stacking sequences are essential for improving the structural performance of composite materials. According to their findings, hybrid composites outperform single fiber composites in terms of stiffness and impact resistance.

The utilization of agricultural waste fibers for sustainable composite manufacture has also been highlighted by recent study. Ali et al. [8] used date palm surface fiber with pineapple leaf fiber to create environmentally friendly hybrid composites. According to their findings, these hybrid composites are appropriate for construction and acoustic applications since they have strong thermal insulation and sound absorption qualities. Additionally, Islam et al. [9] reviewed advancements and challenges in natural fiber reinforced hybrid composites and emphasized that surface modification techniques such as mercerization, silane treatment, and acetylation significantly improve fiber–matrix adhesion and composite performance.

All things considered, current research suggests that hybrid natural fiber composites hold great promise for applications in sustainable engineering. To increase the mechanical performance and long-term durability of these composites, researchers are still investigating better fabrication methods, fiber surface treatments, and nano-reinforcement techniques.

Natural Fiber Hybrid Composites

Combinations of natural and synthetic fibers are used to reinforce polymer matrices to create natural fiber hybrid composites. Several factors affect these composites' performance, such as:

- Type of fiber
 - The direction of fibers
 - The percentage of fiber volume

- The order of stacking
- Surface treatment of fibers

Fiber-matrix adhesion

In addition to improving mechanical performance, proper hybridization lessens its negative effects on the environment. Fig.2 shows Key parameters affecting the performance of natural fiber hybrid composites.

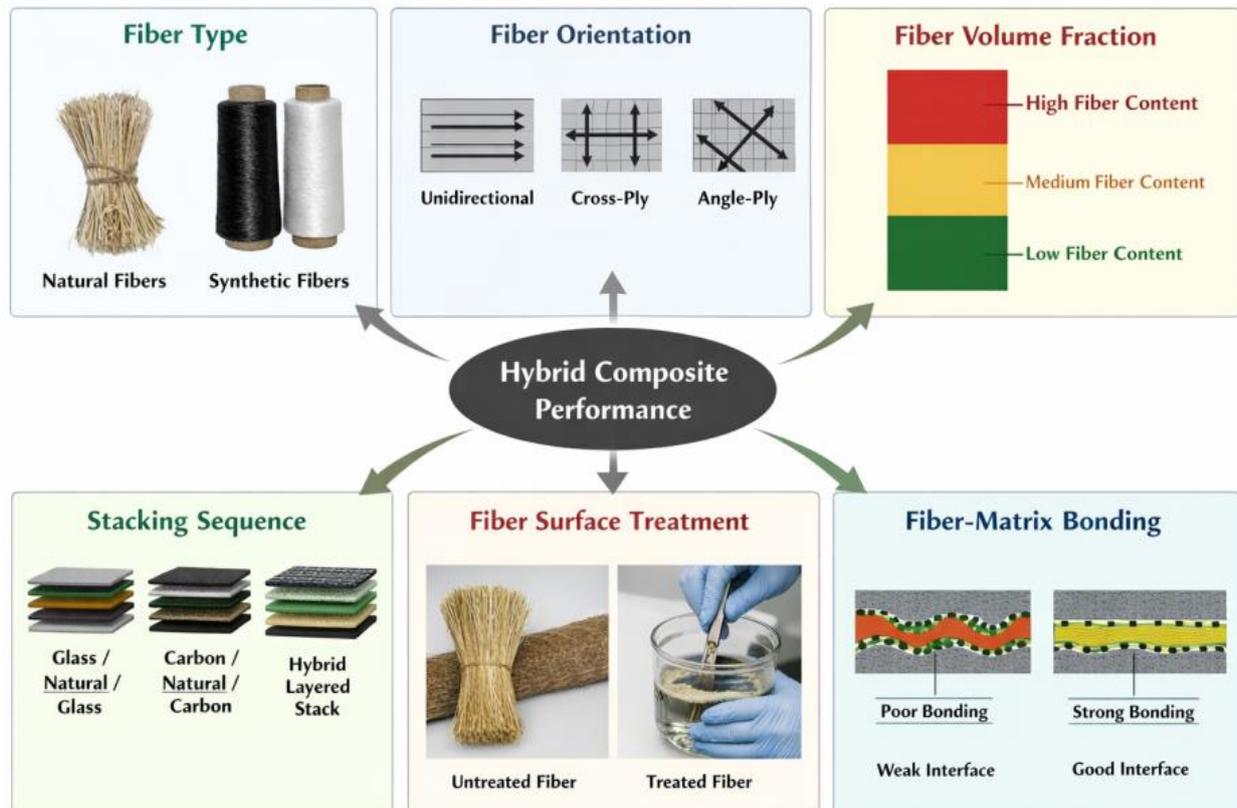


Fig.2 Key parameters affecting the performance of natural fiber hybrid composites

Hybridization of Natural Fibers with Synthetic Fibers

4.1 Flax Fiber Hybrid Composites

Linum usitatissimum is the source of flax fibers, which are bast fibers. These fibers have a moderate tensile strength and decent stiffness. The mechanical performance of flax fiber composites is greatly enhanced by hybridization with glass or carbon fibers.

According to studies, flax composites can have their tensile strength and stiffness increased by incorporating a tiny percentage of carbon fibers. Because of their robust fiber-matrix bonding and fiber bridging mechanisms, flax-glass hybrid composites also exhibit enhanced interlaminar shear strength and fracture toughness.

4.2 Sisal Fiber Hybrid Composites

The leaves of the *Agave sisalana* plant are used to harvest sisal fiber. Because of its accessibility and favorable mechanical qualities, it is frequently utilized in hybrid composites.

Alkali (NaOH) treatment is one example of a chemical treatment that increases bonding with polymer matrices and improves the surface roughness of fibers. When compared to untreated composites, sisal-glass and sisal-carbon hybrid composites exhibit better tensile and flexural qualities.

4.3 Kenaf Fiber Hybrid Composites

Hibiscus cannabinus is the source of kenaf, a bast fiber. It has a low density, a high cellulose content, and good recyclability. Hybrid composites made of kenaf and glass have demonstrated encouraging mechanical qualities for structural uses. However, kenaf fibers' mechanical qualities may deteriorate as a result of moisture absorption. Therefore, to increase durability, surface treatments and appropriate matrix selection are crucial.

4.4 Jute Fiber Hybrid Composites

Because of its inexpensive cost and strong mechanical performance, jute fiber—also referred to as "golden fiber"—is frequently utilized in composite applications. Tensile and flexural strength are greatly increased when glass or carbon fibers are hybridized with jute. Additionally, research shows that adding synthetic fibers to the laminate structure's outer layers increases its moisture resistance and load carrying capacity.

4.5 Banana Fiber Hybrid Composites

Banana fiber has a high cellulose content and is derived from the pseudo-stem of banana plants. These fibers have low density and have strong mechanical qualities. When compared to pure banana fiber composites, banana-glass and banana-carbon hybrid composites exhibit improved tensile strength, flexural strength, and impact resistance. Banana fibers, however, have a propensity to absorb moisture, which could compromise their long-term endurance.

Hybridization Effect of Mechanical Properties

The mechanical properties of hybrid composites reinforced with both natural and synthetic fibers are significantly better than those of single fiber composites.

Important enhancements include of:

Property	Effect of Hybridization
Tensile Strength	Increased due to synthetic fiber reinforcement
Flexural Strength	Improved with proper stacking sequence
Impact Strength	Enhanced due to fiber bridging
Fracture Toughness	Increased because of crack resistance mechanisms
Interlaminar Shear Strength	Improved through strong fiber-matrix bonding

Fiber-matrix adhesion is further improved and composite performance is enhanced by chemical treatments like alkaline treatment.

Advantages and Limitations of Natural Fiber Hybrid Composites

- **Advantages**
 - A lightweight, low-density structure
 - Eco-friendly and biodegradable materials
 - Lower production costs
 - Better mechanical characteristics as a result of hybridization
 - Less of an influence on the environment
 - Natural fibers' ability to absorb moisture
- **Limitations**
 - Chemical treatment is necessary.

- Complicated manufacturing procedures

Hybrid composites have great potential as sustainable engineering materials despite these drawbacks.

Applications

Natural fiber hybrid composites find extensive use in a variety of engineering applications, such as:

- Interior car panels
- Structural elements used in aircraft
- Offshore and marine constructions
- Athletic gear
- Materials for packaging
- Construction and building supplies

These applications profit from hybrid composites' enhanced mechanical qualities and lightweight design.

Future Research

Future studies on natural fiber hybrid composites ought to concentrate on:

- Advanced surface treatments for fibers
- Reinforcement using nanofiller for better qualities
- Enhancement of moisture resistance
- Eco-friendly production methods
- Studies on recyclability and life cycle assessment

These advancements have the potential to improve the functionality and broaden the uses of natural fiber hybrid composites.

Conclusion

For engineering purposes, natural fiber reinforced hybrid composites are a promising class of sustainable materials. Combining natural and synthetic fibers enhances durability, fracture toughness, and mechanical strength while preserving environmental advantages. According to studies, the hybridization ratio, stacking order, and fiber treatment all have a big impact on composite performance. Natural fiber hybrid composites have the potential to partially replace traditional synthetic fiber composites in a number of industrial areas with further study and technologic developments.

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PEG-Doped Mechanochemically Efficient Aqueous Media: Review

Dr. Aakash Singh¹, Dr. Piyush Gupta², Mr. Suraj Bhan Singh Yadav³

¹Department of Applied Science and Humanities, FoET, Lucknow, Uttar Pradesh, India

²Assistant Professor, Department of Mechanical Engineering, , REC Pratapgarh, Uttar Pradesh, India

³Chief Manager, Hindustan Aeronautics Ltd, Korwa, Amethi, Uttar Pradesh, India

ARTICLE INFO

Article History:

Published: 18 March 2026

Publication Issue :

Volume 13, Issue 7

March-April-2026

Page Number :

08-12

ABSTRACT

Mechanochemistry has emerged as an important tool in modern chemical synthesis because it enables chemical transformations through mechanical energy rather than conventional thermal activation. Mechanical energy generated by grinding, milling, or shearing can induce bond breaking and formation in solid or liquid systems, enabling reactions to occur under mild and environmentally friendly conditions.

INTRODUCTION

In recent years, the integration of green solvents and polymer-assisted reaction media has significantly improved the efficiency of mechanochemical processes. Among these additives, Polyethylene Glycol (PEG) has gained considerable attention as a versatile and environmentally benign polymeric medium. PEG-doped aqueous systems provide a unique reaction environment that enhances reaction kinetics, mass transfer, and catalyst stability, making them highly suitable for sustainable chemical synthesis. PEG is a water-soluble, non-toxic, and biodegradable polymer composed of repeating ethylene oxide units. Because of its high polarity and ability to form hydrogen bonds with water and other molecules, PEG behaves as both a solvent and a phase-transfer catalyst in many chemical reactions. Studies have shown that PEG-based solvent systems can replace traditional organic solvents in various organic transformations. For example, a critical review by Robin D. Rogers and co-workers demonstrated that PEG and PEG-containing aqueous solutions can function as environmentally benign reaction media with excellent separation properties and phase-transfer characteristics. These systems enable efficient extraction and recycling of catalysts and products, thereby reducing solvent waste and improving sustainability in chemical processes.

The combination of PEG with water forms a PEG-H₂O mixed solvent system, which has been increasingly used in green synthesis. In such systems, water serves as the primary solvent while PEG acts as a stabilizing and catalytic medium. Research has shown that PEG-water mixtures can significantly enhance reaction rates and

yields due to improved molecular interactions and favorable microenvironments for reactants. Recent studies indicate that PEG–H₂O solvent systems provide high atom economy, mild reaction conditions, and improved product selectivity in a wide range of organic reactions, particularly in the synthesis of heterocyclic compounds and multicomponent reactions.

When PEG-doped aqueous media are used under mechanochemical conditions, the reaction efficiency is further improved. Mechanochemical methods such as ball milling or grinding generate localized high-energy sites that promote chemical transformations. However, the efficiency of these reactions often depends on the mobility and interaction of reactant molecules. The addition of PEG increases the viscosity and structural organization of the aqueous medium, which enhances molecular collisions during mechanical agitation. PEG chains can also stabilize transition states through hydrogen bonding interactions, thereby lowering activation energy and accelerating reaction rates. As a result, PEG-assisted mechanochemical reactions typically show higher yields and shorter reaction times compared with traditional solvent-based methods.

Several studies have demonstrated the effectiveness of PEG as a reaction medium in organic synthesis. For instance, S. Chandrasekhar and co-workers reported the use of PEG as a recyclable solvent in palladium-catalyzed Heck reactions. Their work showed that PEG not only serves as a solvent but also acts as a phase-transfer catalyst, enabling efficient carbon–carbon bond formation with high selectivity and easy catalyst recovery. Similarly, PEG has been successfully used as a recyclable solvent in organocatalytic reactions such as Michael additions, where high yields and stereoselectivities were achieved while maintaining solvent recyclability.

In addition to organic synthesis, PEG-doped aqueous media have been widely used in the synthesis of heterocyclic compounds and functional materials. Research in Green Chemistry reported the synthesis of 1,3,5-triazines using PEG-600 as a green solvent with molecular oxygen as an oxidant. The process demonstrated excellent yields, simple work-up procedures, and the ability to recycle the PEG solvent for multiple cycles. Other studies have shown that PEG can enhance reactivity and selectivity in the synthesis of complex organic molecules such as pyrrolo-isoxazoles and triazole derivatives. In these reactions, PEG acts as both a solvent and a reaction promoter, improving product formation under mild conditions while maintaining environmental compatibility.

Another important advantage of PEG-doped aqueous systems is their ability to stabilize nanoparticles and catalytic species during mechanochemical synthesis. The polymer chains of PEG can adsorb on particle surfaces and prevent agglomeration, thereby controlling particle size and morphology. This property has been particularly useful in the synthesis of metal nanoparticles and nanocomposite materials, where PEG acts as a stabilizing agent and dispersant. The presence of PEG also facilitates uniform energy transfer during mechanical milling, which enhances the formation of homogeneous nanostructures. From a sustainability perspective, PEG-doped mechanochemical aqueous media align well with the principles of green chemistry. The use of water as the primary solvent minimizes environmental hazards, while PEG is biodegradable and reusable. The combination of mechanochemistry with PEG-based solvent systems reduces the need for toxic organic solvents, decreases energy consumption, and simplifies product separation and purification. Furthermore, PEG can often be recovered and reused without significant loss of catalytic activity, making the overall process more economical and environmentally friendly.

Additional Discussion: Role of Water and Other Solvents in Mechanochemical Reactions

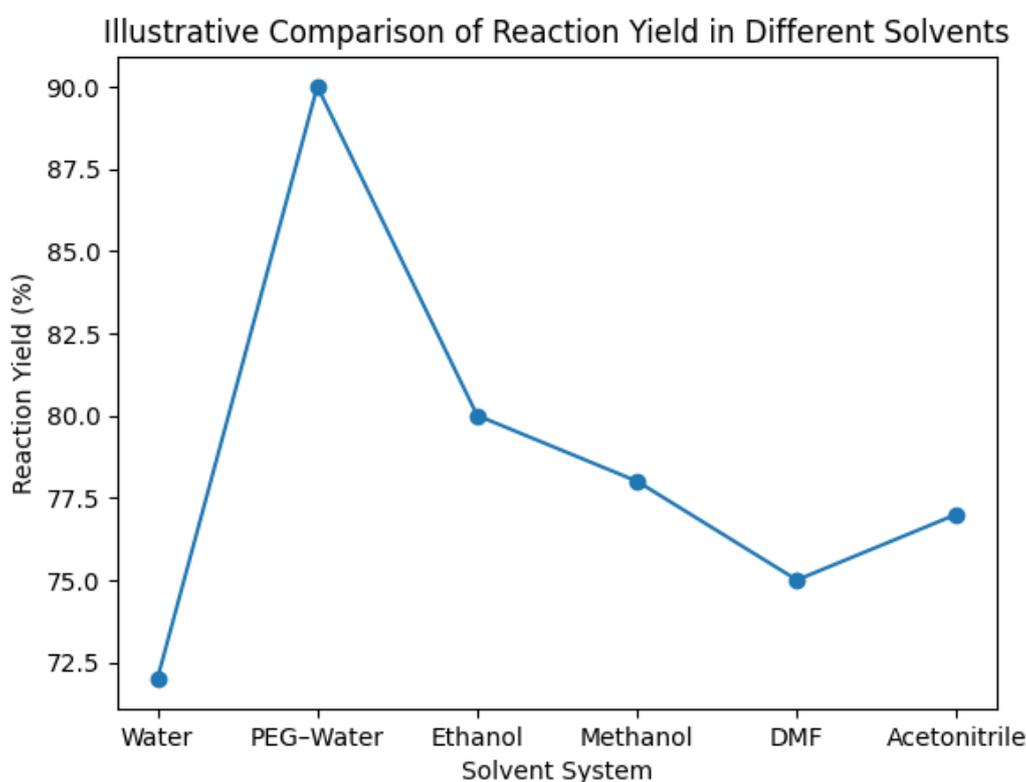
Water has emerged as one of the most important solvents in green chemistry due to its abundance, non-toxicity, low cost, and environmentally benign nature. In mechanochemical and polymer-assisted reaction systems, water provides a unique reaction environment that promotes sustainable chemical synthesis. Unlike traditional organic solvents, water possesses high polarity and strong hydrogen-bonding capability, which facilitates the stabilization of ionic intermediates and transition states during chemical reactions. When used alone in mechanochemical processes, water can improve reactant mobility and enable better dispersion of solid particles during grinding or milling. However, pure water sometimes exhibits limitations such as poor solubility for non-polar reactants and limited compatibility with certain catalysts. To overcome these challenges, researchers often combine water with additives or co-solvents such as Polyethylene Glycol (PEG). PEG-water mixtures create a microstructured environment that enhances mass transfer, increases reactant solubility, and improves reaction efficiency under mechanical activation. The polymer chains of PEG interact with water molecules through hydrogen bonding, producing a semi-structured solvent network that can stabilize reactive intermediates and improve catalytic activity. As a result, PEG-doped aqueous media often exhibit higher reaction yields and faster kinetics compared with reactions carried out in pure water.

In contrast, many traditional organic solvents such as ethanol, methanol, dimethylformamide (DMF), and acetonitrile have long been used in organic synthesis because of their ability to dissolve a wide range of reactants and catalysts. Alcohol-based solvents like ethanol and methanol are moderately polar and can participate in hydrogen bonding, which makes them suitable for many condensation and substitution reactions. However, these solvents are volatile and flammable, which raises safety and environmental concerns during large-scale industrial processes. Polar aprotic solvents such as DMF and acetonitrile are widely used in synthetic chemistry because they dissolve both organic and inorganic compounds effectively and can enhance reaction rates in nucleophilic reactions. Despite these advantages, such solvents are often toxic, expensive to dispose of, and harmful to the environment. Additionally, in mechanochemical systems where grinding or milling is involved, the use of volatile solvents may reduce energy transfer efficiency because the solvent can dampen mechanical impacts. For these reasons, researchers are increasingly replacing conventional organic solvents with greener alternatives such as water, PEG-water mixtures, ionic liquids, and deep eutectic solvents. Among these options, PEG-water systems have proven particularly attractive because they combine the advantages of water with the solubilizing and catalytic properties of PEG. Consequently, many recent studies report improved reaction yields, better catalyst stability, and simplified product separation when PEG-doped aqueous media are used instead of conventional organic solvents.

Comparison of Water, PEG–Water, and Other Common Solvents

Solvent System	Polarity	Environmental Impact	Reactant Solubility	Mechanochemical Efficiency	Recyclability
Water	High	Very low toxicity, eco-friendly	Moderate	Moderate	Easy
PEG–Water Mixture	High	Green and biodegradable	High	Very high	Excellent
Ethanol	Moderate	Flammable but	High	Moderate	Moderate

Solvent System	Polarity	Environmental Impact	Reactant Solubility	Mechanochemical Efficiency	Recyclability
		relatively green			
Methanol	Moderate	Toxic and volatile	High	Moderate	Moderate
Dimethylformamide (DMF)	High	Toxic and hazardous	Very high	Moderate	Difficult
Acetonitrile	Moderate–High	Toxic and volatile	High	Moderate	Limited



Graph: Evaluation of reaction yield obtained using different solvent

"Key observations • PEG–water systems generally show higher reaction efficiency due to improved mass transfer and stabilization of intermediates. • Water alone is the most environmentally friendly solvent, but may have solubility limitations. • Organic solvents often provide good solubility but higher toxicity and environmental impact. • PEG-doped aqueous media combine green chemistry advantages with improved reaction performance.

The graph above illustrates a typical comparison of reaction yield obtained using different solvent systems in a mechanochemical reaction. In many reported studies, PEG-water mixtures provide the **highest yield and reaction efficiency** because the polymer chains enhance molecular collisions during mechanical agitation and stabilize the transition states of the reaction.

Conclusion

Overall, the literature demonstrates that PEG-doped mechanochemically efficient aqueous media represent a promising approach for sustainable chemical synthesis. The unique physicochemical properties of Polyethylene Glycol, including its hydrogen-bonding capability, phase-transfer behavior, and recyclability, enable improved reaction kinetics and selectivity under mechanochemical conditions. As research in green chemistry continues to expand, PEG-assisted mechanochemical systems are expected to play an increasingly important role in organic synthesis, nanomaterial fabrication, and environmentally responsible chemical processing.

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Performance Analysis of Thermal Energy Storage System

Akash Bajpai, Rajesh Kumar

Assistant Professor, Department of Mechanical Engineering, FoET, DSMNRU, Lucknow, Uttar Pradesh, India

ARTICLE INFO

Article History:

Published: 18 March 2026

Publication Issue :

Volume 13, Issue 7
March-April-2026

Page Number :

13-15

ABSTRACT

Thermal Energy Storage (TES) systems play a vital role in improving energy efficiency and enabling the integration of renewable energy sources. TES allows excess thermal energy to be stored during periods of low demand and released during peak demand. This paper presents a detailed performance analysis of a thermal energy storage system focusing on charging and discharging characteristics, thermal efficiency, storage capacity, and heat loss behavior. Sensible heat storage and latent heat storage techniques are analyzed for their energy storage capability and operational effectiveness. Experimental and theoretical evaluation methods are discussed to analyze system performance under different operating conditions. The results indicate that optimized TES systems significantly improve energy utilization and reduce energy wastage in industrial and renewable energy applications. The study also highlights the importance of proper insulation, selection of storage materials, and heat transfer enhancement methods for improving TES performance.

Keywords: Thermal Energy Storage, Sensible Heat Storage, Latent Heat Storage, Phase Change Materials, Renewable Energy, Energy Efficiency.

INTRODUCTION

Energy demand has been increasing rapidly due to industrial growth and population expansion. Traditional energy resources such as fossil fuels are limited and cause environmental pollution. Renewable energy sources like solar and wind energy are increasingly used to address these issues. However, these energy sources are intermittent and require efficient storage systems to ensure a stable energy supply.

Thermal Energy Storage (TES) is an effective technology that allows energy to be stored in the form of heat for later use. TES systems help in balancing energy demand and supply, improving system reliability and efficiency. They are widely used in solar thermal power plants, industrial processes, district heating systems, and building energy management systems.

Literature Review

Several researchers have contributed to the development of thermal energy storage technologies. Dincer and Rosen emphasized the importance of TES systems in sustainable energy systems. Sharma et al. studied phase change materials and highlighted their high energy storage density.

Recent research focuses on nano-enhanced phase change materials, advanced heat exchanger designs, and improved insulation techniques to enhance system performance. Despite these improvements, challenges such as low thermal conductivity of PCMs and high initial system cost remain significant issues in TES development.

Types of Thermal Energy Storage Systems

Thermal energy storage systems are generally classified into three categories:

1. Sensible Heat Storage – Energy is stored by increasing the temperature of a storage medium.
2. Latent Heat Storage – Energy is stored during phase change processes using phase change materials.
3. Thermochemical Storage – Energy is stored through reversible chemical reactions.

Each storage technique has its advantages and limitations depending on the application and operating conditions.

Methodology

The performance evaluation of the TES system involves experimental setup and theoretical calculations. The main components of the experimental system include a storage tank, heat exchanger, heating source, insulation layer, and temperature measurement devices.

The charging process involves transferring heat to the storage medium while the discharging process involves extracting stored heat for useful applications. Temperature data is recorded at different time intervals to evaluate system performance.

Performance Parameters

The following parameters are considered for evaluating TES system performance:

- Thermal storage capacity
- Charging efficiency
- Discharging efficiency
- Heat loss rate
- Overall system efficiency

Thermal efficiency is calculated based on the ratio of useful energy recovered to the total energy supplied to the system.

Results and Discussion

Experimental observations show that sensible heat storage systems provide stable performance with simple system design. Latent heat storage systems offer higher storage density and maintain nearly constant temperature during phase change.

Improved insulation significantly reduces thermal losses. The use of heat transfer enhancement techniques such as fins or nano-enhanced materials improves system efficiency. The results demonstrate that optimized TES systems can improve overall energy utilization.

Applications

Thermal Energy Storage systems are widely used in:

- Solar thermal power plants
- Industrial waste heat recovery
- Air conditioning systems

- District heating systems
- Building energy management systems

These applications help reduce peak load demand and improve energy efficiency.

Advantages

Major advantages of TES systems include:

- Improved energy efficiency
- Reduced energy consumption
- Enhanced renewable energy utilization
- Reduced greenhouse gas emissions
- Stable and reliable energy supply

Conclusion

Thermal Energy Storage systems are essential for improving energy management and supporting renewable energy integration. The performance analysis presented in this study shows that TES systems significantly improve energy utilization and reduce thermal losses.

Future research should focus on advanced phase change materials, improved heat transfer designs, and cost-effective storage technologies to enhance the large-scale implementation of TES systems.

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Future Solutions and Challenges for Solar Energy Producing Devices

Aditi Singh¹, Dr. Prashant Kumar Srivastava², Dr. Rakesh Verma³

¹Department of Mechanical Engineering, FoET, Lucknow, Uttar Pradesh, India

²Associate Professor, Department of Mechanical Engineering, AIMT, Lucknow, Uttar Pradesh, India

³Assistant Professor, Department of Mechanical Engineering, FoET, DSMNRU, Lucknow, Uttar Pradesh, India

ARTICLE INFO

Article History:

Published: 18 March 2026

Publication Issue :

Volume 13, Issue 7
March-April-2026

Page Number :

16-22

ABSTRACT

Major developments, as well as remaining challenges and the associated research opportunities, are evaluated for three technologically distinct approaches to solar energy utilization: solar electricity, solar thermal, and solar fuels technologies. Much progress has been made, but research opportunities are still present for all approaches. Both evolutionary and revolutionary technology development, involving foundational research, applied research, learning by doing, demonstration projects, and deployment at scale will be needed to continue this technology-innovation ecosystem.

This paper deals with the necessary information regarding solar thermal conversion systems and solar photovoltaic conversion systems or the combination of both for commercial and domestic purposes. The more prevalent solar conversion techniques consist of solar water heating, solar air heating, solar thermal power plants, solar air conditioning and refrigeration, etc., while solar photovoltaic system (SPS) converts incident solar radiation into electrical energy by using solar cell consisting of semiconductor materials. In brevity to understand the depth of solar energy conversion process as incredible utility, some past and ongoing research details have also been mentioned. Moreover, many recent developments and future aspects have been discussed about solar energy in terms of applications, challenges, and requirement to focus on the utilization of sun's energy as promising, sustainable, economical, and environmental-friendly renewable source.

Keywords: SPS, photovoltaic cells

INTRODUCTION

Today the consumption of energy is increasing every second but today's resources i.e. fossil fuel, is limited, will be exhausted sooner or later, also global warming and pollution create acute problems due to its use[1]. Today we need to think about the renewable and environment friendly source of energy to save the future society, this can be possible on the base of solar energy[2].

Sun is an inexhaustible source of energy capable of fulfilling all the energy needs of humankind. The energy from the sun can be converted into electricity or used directly. Electricity can be generated from solar energy either directly using photovoltaic (PV) cells or indirectly using concentrated solar power (CSP) technology. Progress has been made to raise the efficiency of the PV solar cells that can now reach up to approximately 34.1% in multi-junction PV cells[1]. Electricity generation from concentrated solar technologies has a promising future as well, especially the CSP, because of its high capacity, efficiency, and energy storage capability. Solar energy has a bright future because of the technological advancement in this field and its environment-friendly nature. The biggest challenge however facing the solar energy future is its unavailability all-round the year, coupled with its high capital cost and scarcity of the materials for PV cells[4]. These challenges can be met by developing an efficient energy storage system and developing cheap, efficient, and abundant PV solar cells[29]. This article discusses the solar energy system as a whole and provides a comprehensive review on the direct and the indirect ways to produce electricity from solar energy and the direct uses of solar energy. However, several challenges still limit the large-scale adoption of these technologies[15]. This research paper aims to analyze current solar energy producing devices, identify research gap in recent studies, and propose solutions for improving solar energy systems[9]. The technical, economic, environmental, and storage-related challenges are discussed with possible solutions. Furthermore, a comprehensive list of future potential research directions in the field of direct and indirect electricity generation from solar energy is proposed[8].

Literature Review

Improved technologies for harnessing solar energy are not limited to creating more efficient solar cells[4]. The associated hardware of delivering power from solar cells to homes and businesses, and storing this intermittent resource on the grid, offer R&D opportunities. Lewis reviews the status of these areas, as well as solar thermal and solar fuels approaches for harnessing solar energy[6].

The costs of Si-based solar panels have declined so rapidly that panel costs now make up <30% of the costs of a fully installed solar-electricity system[7]. Research and development (R&D) opportunities hence lie in the development of very high efficiency conversion materials, to advantageously leverage the associated reduction in area-related balance-of-systems costs. Such materials would optimally either leverage or mate with existing, low-cost Si photovoltaic (PV) technology[10]. Ultralightweight, flexible, robust, and efficient materials could also greatly reduce the installation costs and could allow for enhanced automation and inexpensive support structures[11].

The development of cost-effective persistent grid-scale storage to compensate for the intermittency of sunlight is a major area for R&D. Possibilities include new types of batteries and flow batteries, as well as geologic storage of hydrogen, methane, or compressed air[11].

Opportunities also exist to improve the capabilities of concentrated solar power systems that convert sunlight into heat. Improved thermal storage fluids would provide longer-term storage to compensate for cloudy days in areas of high direct insolation.

Solar cells are mainly described based on their architecture; some consist mostly of metals (inorganic thin films), some nanomaterials (QD), some polymers (referred to as organic), etc. Traditionally, solar cells are electronic devices focused on converting sunlight into direct electrical energy because of the photoelectric effect from metals and inorganic semiconductors [4]. Figure 1 below shows a typical p-n junction silicon solar cell. The generation of electricity comes from the photons (light particles) when sunlight energy shines on the cell.

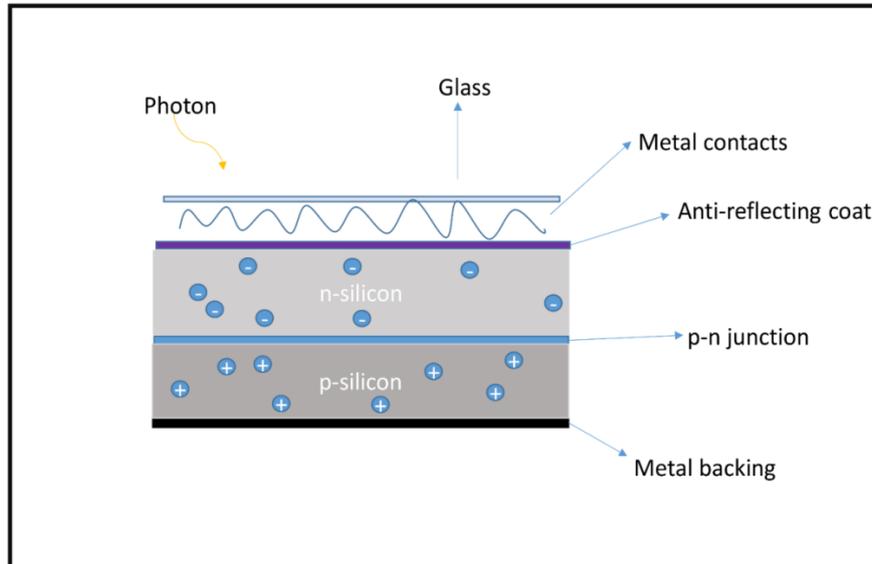


Figure 1: Schematic structure of typical a silicon solar cell [4].

Research Gap

1. Material Stability Issues such as Perovskite materials degrade when exposed to moisture, oxygen, heat, and ultraviolet light. and also, device performance decreases over time limiting commercial use.
2. Solar devices may produce 10–25% less power in practical conditions compared to lab results
3. Efficiency Loss in Real-World such as temperature fluctuations, dust accumulation, Shading effects and weather variability
4. Some solar devices use toxic or rare materials, such as Lead (in perovskite cells), Cadmium (in thin-film solar cells)
5. Technologies like flexible solar cells, organic photovoltaics, and perovskite devices have not yet reached large-scale commercial production.
6. Flexible and lightweight solar devices often face mechanical reliability issues such as sensitivity to bending or mechanical stress

Methodology

Two factors responsible for the amount of radiation that is received by a solar panel surface are its orientation and tilt angle. The tilt angle is defined as the angle between the solar panel surface and the horizontal plane. The orientation of the solar panel is also defined with respect to the horizontal plane and it is the angle between the line due south and the projection of the solar panel normal to the surface on the horizontal plane. It has been widely acknowledged that the optimum orientation for a solar panel, in the northern hemisphere, is facing due south. For the choice of the optimum tilt angle, however, there have been several widely diverse proposals[4].

The solar radiation model is subsequently used to determine the optimum tilt angle by taking into account the frequency and intensity of the cloud cover. The tilt angle is chosen that optimizes the beam radiation on clear days and the diffuse radiation on overcast days. Finally, the effect of different load profiles on the optimum tilt angle will also be discussed.

In recent years, many theories for the production of solar thermal hydrogen have been established. The main thermo-chemical ideas include methane splitting, solar natural gas steam reformation, and solar thermo-chemical processes. Additionally, pure hydrogen can be created utilizing solar heat and renewable power via the electrochemical technique of high-temperature electrolysis. Over the last several years, significant progress has been made in the development of solar thermal techniques for the creation of hydrogen. Different process models were examined, and design ideas and test facilities may be realized. Le Naour et al. (2005), Zhang et al. (2014) provides a summary of the current state of the art and research problems in high-temperature hydrogen generation. Technologies as the primary or only source of high-temperature thermal applications. A concentrator system for a solar thermal plant includes a circular solar collector that directs solar energy onto a receiver located on a tower. The receiver includes a heat-exchanging mechanism or a chemical reactor. The fundamental ideas behind the processes under consideration are shown in Figure 2.

The incorporation of modern technologies, such as membranes and membrane reactors, concentrating solar power systems, and molten salt heat carriers, permits the partial decarbonization of fossil fuels and the transfer of solar energy via the existing natural gas infrastructure. Kim et al. (2018) offer a cost-effective method for producing hydrogen and capturing emissions centered on a methane hydrogen production pathway using a composite membrane reactor. To adequately recover hydrogen and concentrate carbon dioxide, a membrane that was both highly permeable and moderately selective was used[4].

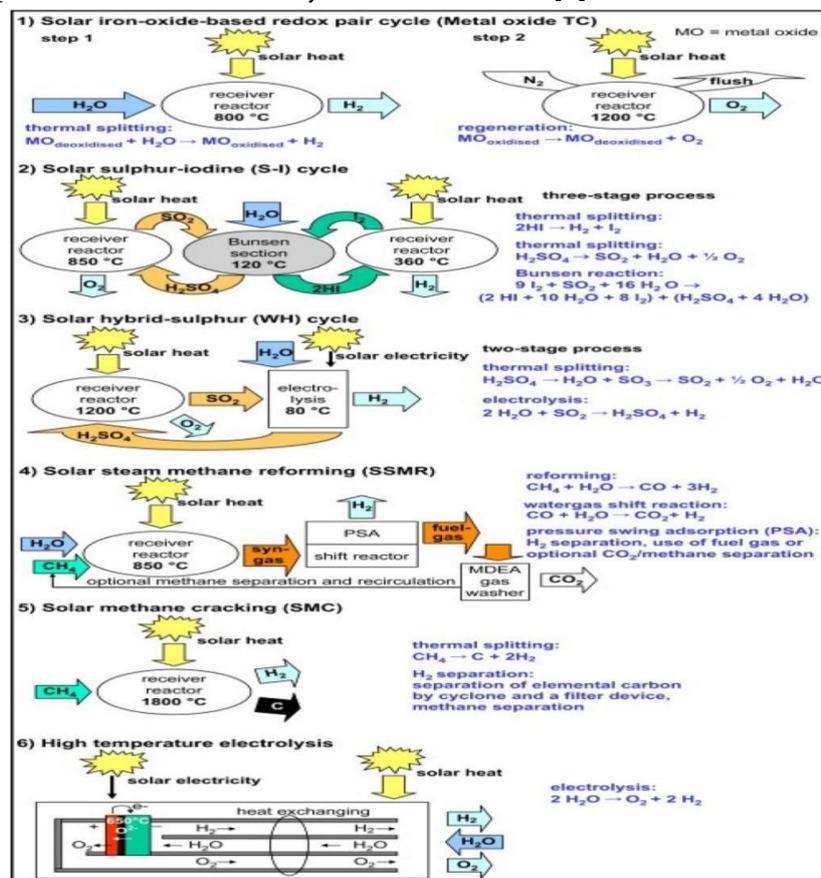


Figure 2: The fundamentals of solar thermal hydrogen production systems

Results and Discussion

1. Perovskite Solar Cells have a high efficiency (>25%) along with lightweight and flexible designs
2. Multiple semiconductor layers can help to increase efficiency of the system up to 47% in advanced designs
3. Combination of perovskite materials and silicon can be used in hybrid systems to increase efficiency.
4. Advanced manufacturing methods such as roll-to-roll printing and thin-film fabrication can reduce production costs and enable large-scale deployment of solar energy devices

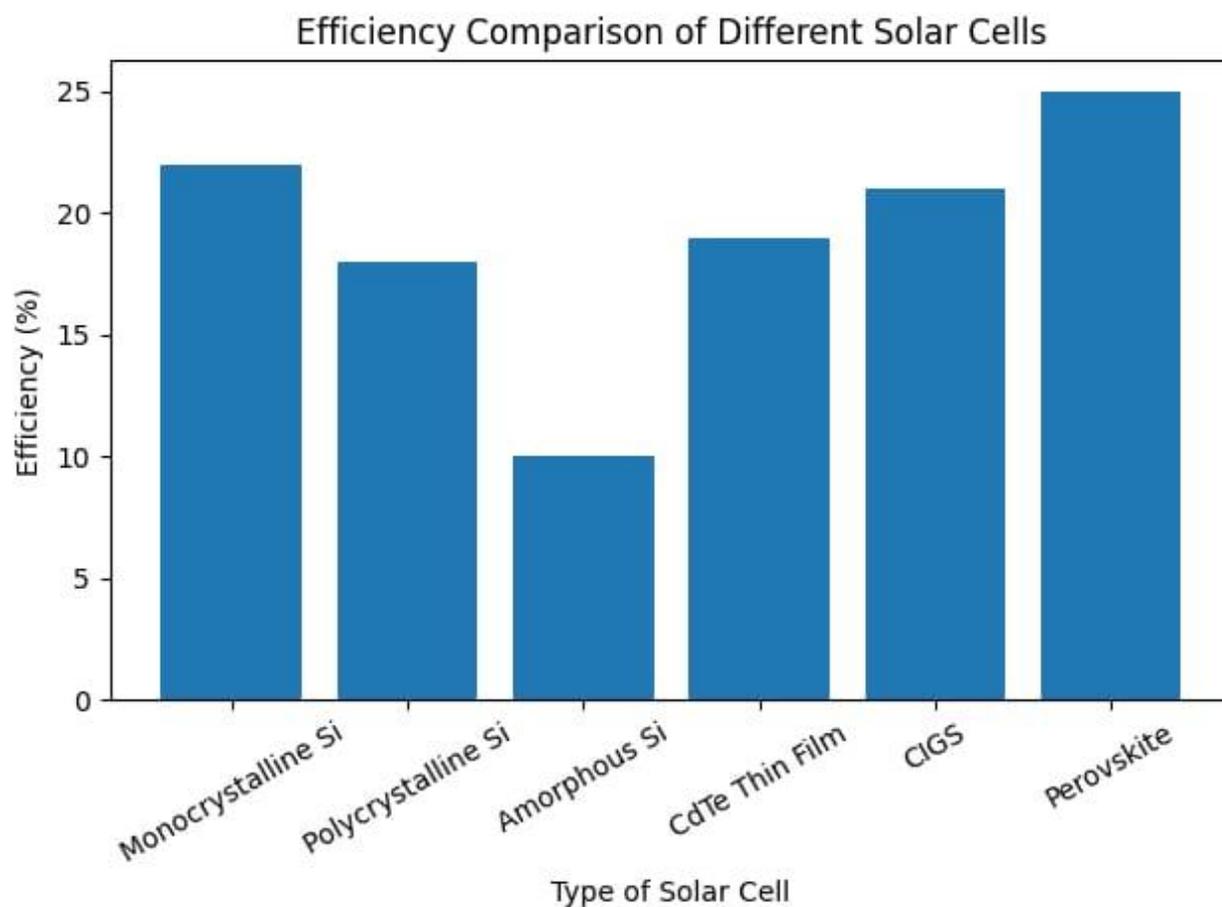


Figure 3: Bar chart comparing the efficiencies of different types of solar cells (Monocrystalline Si, Polycrystalline Si, Amorphous Si, CdTe Thin Film, CIGS, and Perovskite).

Conclusion

Solar energy producing devices play a crucial role in the global transition toward sustainable and renewable energy systems. Technological advancements in device architect and photovoltaic materials have significantly improved solar cell efficiency. There are however countless challenges ahead including environmental concerns, material stability, and real-world performance limitations.

To address these challenges we require a multidisciplinary approach involving material science , energy management technologies, and engineering. By improving integrating energy storage systems, device stability, developing environmentally friendly materials, and reducing manufacturing costs, solar energy technologies can be used widely and contribute significantly to sustainable global development.

Future Scope

1. Improving the stability of solar cells can be achieved through material engineering and advanced encapsulation techniques. Protective coatings and improving device architectures can protect solar cells from ultraviolet radiation and moisture.
2. Hybrid systems combining advanced battery technologies and photovoltaic devices can improve energy reliability. Future research should focus on integrating solar panels with solid-state batteries, hydrogen energy storage systems, or lithium-ion batteries.
3. The use of Internet of Things (IoT) technologies and artificial intelligence can improve solar energy management. Smart monitoring systems can predict power output, optimize system performance, and detect faults in solar installations.
4. Developing lead-free and recyclable solar materials can reduce environmental hazards. Researching improved recycling techniques and alternative semiconductor materials will make solar technologies more sustainable.

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AI and IoT Based Predictive Maintenance System for Industrial Machines

Aditya Shukla¹, Dr. Prashant Kumar Srivastava², Dr. Vivekanand Shukla³

¹Department of Mechanical Engineering, FoET, DSMNRRU Lucknow, Uttar Pradesh, India

²Associate Professor, Department of Mechanical Engineering, AIMT, Lucknow, Uttar Pradesh, India

³ Department Of Mechanical Engineering, DDU Gorakhpur University

ARTICLE INFO

Article History:

Published: 18 March 2026

Publication Issue :

Volume 13, Issue 7

March-April-2026

Page Number :

23-31

ABSTRACT

The following research paper discusses an Internet of Things-based predictive maintenance system for industrial machines. In general, an artificial intelligence and machines' usage results in machine wear, overheating, vibration issues, and unexpected failures, thereby leading to production downtime and financial losses. Traditional methods like reactive and preventive maintenance are not efficient, as they either result in failures or scheduled maintenance. For overcoming these issues, predictive maintenance has become an essential tool.

An Internet of Things-based predictive maintenance system for industrial machines. In general, an artificial intelligence and machines' usage results in machine wear, overheating, vibration issues, and unexpected failures, thereby leading to production downtime and financial losses. Traditional methods like reactive and preventive maintenance are not efficient, as they either result in failures or scheduled maintenance. For overcoming these issues, predictive maintenance has become an essential tool.

Keywords: Predictive Maintenance, IoT, Artificial Intelligence, Industry 4.0, Machine Monitoring.

INTRODUCTION

Industrial machines are very vital in the modern manufacturing and production industry. These machines, such as motors, pumps, turbines, compressors, and other production machines, operate continuously to enhance productivity and efficiency in the industry. However, owing to the continuous nature of these machines, they are often subjected to a number of mechanical issues, such as vibration, overheating, friction, and wear. If these issues are not identified at an early stage, they may lead to failure of machines, resulting in financial losses for the industry. Therefore, monitoring and early detection of these issues in machines have emerged as a significant requirement in the modern industry [1].

Traditionally, two major maintenance strategies have been used by industries, namely reactive maintenance and preventive maintenance. In reactive maintenance, machines are repaired after a failure occurs. Although the concept is simple, the machines may fail suddenly, and the repair costs may be high. In preventive

maintenance, maintenance activities are carried out at regular intervals irrespective of the condition of the machines. Although this method reduces the chances of sudden failure, it may also result in performing unnecessary maintenance activities, thus increasing operational costs. Therefore, traditional maintenance strategies are inefficient in today's high-speed industrial environment [3].



Fig 1 : Smart manufacturing system in industry 4.0

Due to the rapid advancement in digital technologies and the advent of Industry 4.0, industries are shifting towards smarter maintenance strategies. Predictive maintenance is a new and advanced maintenance strategy. This new maintenance strategy is based on monitoring the real-time condition of the machines and predicting potential failure [2]. Predictive maintenance systems use Internet of Things (IoT) technology, Artificial Intelligence (AI) technology, cloud computing, and machine learning algorithms.

The Internet of Things (IoT) technology facilitates the collection of data in real time from the machines in the industries using various types of sensors. For example, vibration sensors, temperature sensors, pressure sensors, and current sensors are installed on the machines. These sensors collect important data regarding the machines and communicate the data using IoT technology. The data is sent to the cloud platform where it can be processed and stored more efficiently [1,3].

The role of artificial intelligence and machine learning algorithms is significant while analyzing the collected data and identifying the abnormalities in the machines. The algorithms use the historical data of the machines and the data collected in real time to predict the failures of the machines. This helps the maintenance engineers to take precautions and avoid the damages to the machines. Thus, the industries become more efficient in maintaining the machines and improving the production efficiency [4].

The main contributions of the study are as follows:

- Development of an AI and IoT-based predictive maintenance framework:

The present study proposes a smart framework that uses IoT sensors and artificial intelligence techniques to monitor the machines in industries. Such a system helps in the continuous monitoring and analysis of the machines.

- Real-time monitoring of machines using sensor technology:

The proposed system uses sensors like vibration sensors and temperature sensors to continuously monitor the machines in industries. Such a system helps in the continuous monitoring of the machines.

- Intelligent fault detection using machine learning techniques:

The proposed system uses machine learning techniques to analyze the data from the sensors. These techniques help in the detection of patterns related to the faults in the machines.

- Reduction of maintenance cost and downtime:

The proposed system helps in the early detection of faults in the machines. Such a system helps in the prevention of sudden breakdown of machines.

- Support for Industry 4.0 and smart manufacturing systems:

The integration of IoT devices and AI technologies enables the development of smart factories where machines can be monitored and controlled automatically.

In this research paper, an AI and IoT based predictive maintenance system for industrial machinery is proposed to improve machine reliability, reduce maintenance costs, and enhance overall industrial productivity [5].

Literature Review

Predictive maintenance has attracted considerable attention in recent times, particularly with the rapid advancement of Industry 4.0 technologies, such as IoT, AI, and cloud computing. Various researchers have presented different methods for monitoring and predicting the conditions and faults in machines, enabling predictive maintenance [3,2].

Mansa K., Apoorva Joshi, Vinay L., and A. Mallikarjuna Reddy presented a research paper titled “Predictive Maintenance of Industrial Machines Using IoT” published in the International Journal of Research (IJR). In the research paper, the authors presented a monitoring system for industrial machines using IoT technology. In the system, sensors such as vibration sensors and temperature sensors are used to monitor the conditions of the machines in real-time [1]. The data is then sent to a cloud server for analysis, enabling the detection of abnormal conditions in the machines.

According to the authors, predictive maintenance has shown promising results in reducing unexpected machine downtime, thereby improving productivity in industrial setups. The research was centered on machine monitoring and data analysis via sensors [1,2].

The second research was conducted by Naga Hemanth, B. Mahesh Babu, and K. Kalyan Raj in 2023 and published in the International Journal of Research Publication and Reviews (IJRPR). The research was published in the paper titled “IoT-Based Predictive Maintenance System for Industrial Machinery.” According to the research, predictive maintenance has shown promising results in reducing costs and improving machine reliability in industrial setups. In the research, machine parameters, including vibration, temperature, and pressure, were monitored via sensors connected to microcontrollers. The data was transmitted to cloud servers, and machine learning algorithms were applied to predict machine faults. According to the research, predictive maintenance can be beneficial in improving machine reliability and reducing costs in industrial setups [6].

In another research, Lee, Bagheri, and Kao (2015) presented a discussion on the concept of cyber-physical systems in the context of Industry 4.0 in their research article published in Manufacturing Letters. According to the research, the concept of smart sensors, IoT technology, and intelligent systems of data analysis can be combined in a manner that creates a smart environment in industries. It is clear from the research that predictive maintenance of equipment is one of the most important applications of Industry 4.0 technology. It is possible to monitor the performance of machinery in industries through the integration of machinery with digital systems of monitoring [5,4].

Similarly, research on predictive maintenance using machine learning techniques was conducted by Carvalho et al. (2019). The research used various machine learning techniques such as decision trees, neural networks, and support vector machines in predicting faults in industrial machinery. According to the research findings, machine learning techniques can be used in analyzing machine faults and predicting early signs of failure. It was concluded that predictive maintenance using AI techniques can be effective in improving the reliability of machinery [7].

Although various studies have been conducted on predictive maintenance using IoT and machine learning techniques, various challenges have remained unsolved. These challenges include dealing with large amounts of sensor data, ensuring the security of communication between devices, and improving the accuracy of machine learning techniques. Therefore, a need arises for an integrated system using IoT technology in predictive maintenance [4,1].

The aim of the research in the present chapter is to propose an AI and IoT-based predictive maintenance technique for industrial machinery. The proposed technique will use various sensor technologies and IoT communication networks, and machine learning algorithms for monitoring the conditions of the machine and predicting any fault that may occur in the future [3].

Methodology

The methodology of the research is based on the development of a predictive maintenance system for industrial machines using Artificial Intelligence and Internet of Things technologies. The main aim of the system is to continuously monitor the conditions of the machine and detect any wear that may occur in the future. There are many studies related to predictive maintenance systems in the context of smart manufacturing environments. Lee, Bagheri, and Kao (2015) stated that the integration of cyber-physical systems with industrial machines is useful for intelligent monitoring and maintenance in Industry 4.0 environments [6,5].

In industrial systems, various machines such as electric motors, pumps, air conditioning systems, and production machines are used. These machines are used for a long time without any interruption. Such continuous usage of industrial machines may cause various problems such as high vibrations, overheating, lubricating oil failure, and mechanical wear. These problems may cause sudden machine breakdown if not detected in the initial stages. Mobley (2002) stated that monitoring various parameters such as vibrations, temperature, and pressure is an efficient method to identify mechanical faults in industrial systems [4].

In the proposed system, sensors are used to monitor various parameters such as vibrations, temperature, and pressure in industrial systems. Sensors such as vibration sensors, temperature sensors, and pressure sensors are used to collect data during machine operation. These sensors help to identify various abnormal conditions such as high vibrations or sudden increase in temperature during machine operation. Such types of sensor-based systems for industrial machine monitoring are also discussed by Carvalho et al [2]. (2019) in their research article on machine learning techniques for industrial machine maintenance.

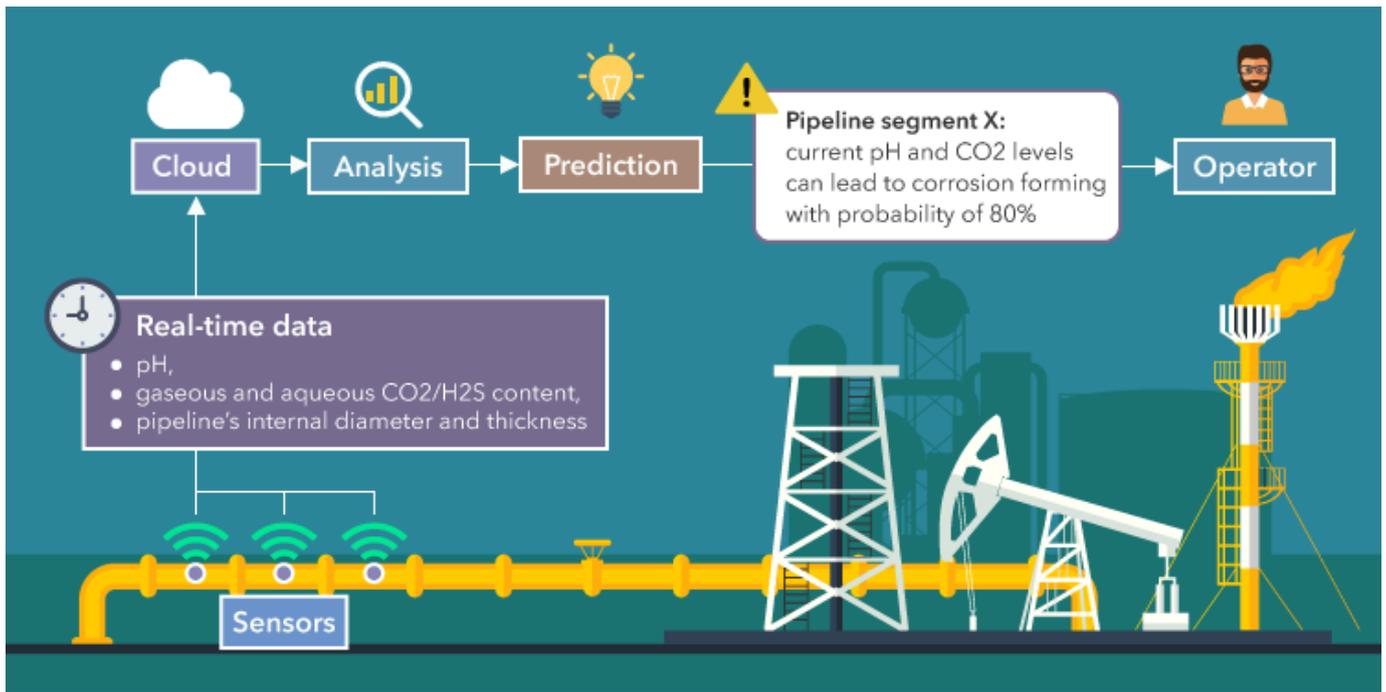


Fig 2: IOT for predictive maintenance oil and gas

The data from the sensors is collected and sent to an IoT microcontroller, such as Arduino and ESP32. This microcontroller is a data acquisition system that processes data from sensors and sends it to a cloud platform. According to Zonta et al. (2020), IoT devices have a significant role in collecting and sending data from industrial machines in a smart manufacturing system [1].

The IoT device sends the collected data from the industrial machine to a cloud server using wireless communication methods, such as Wi-Fi and GSM networks. The data is stored in a database in the cloud, where it is easily accessed and monitored by engineers. Engineers use monitoring systems to view the status of the industrial machines [5].

When the data is stored in the cloud, Artificial Intelligence and Machine Learning algorithms are used to analyze the data from the sensors. These algorithms compare the data from the industrial machines with the data from the sensors. This comparison is used to determine the status and conditions of the machines.

historical data to identify abnormal patterns. For example, an increase in vibration level may indicate wear in bearings, while a sudden increase in temperature may indicate overheating or lubrication failure [8].

If abnormal machine conditions are identified by the system, a predictive maintenance notification is sent to maintenance engineers. The notification is sent through various means such as a dashboard, mobile application, or email. The engineers can check the machine and perform maintenance work before a major failure occurs.

The proposed methodology enhances machine reliability, minimizes maintenance cost, and reduces unexpected machine downtime. The proposed system is also beneficial for implementing smart factories and intelligent manufacturing systems according to Industry 4.0 concepts [1,7].

Flow Process of the Proposed System

- The working process of the proposed predictive maintenance system can be explained as follows:
- Machine Operation – Industrial machines are continuously operating in a manufacturing environment.
- Sensor Monitoring – Vibration, temperature, and pressure sensors are used for monitoring the machine's status.

- Data Collection – Real-time data is collected from the machine by the sensor, i.e., vibration level, temperature value, and pressure conditions.
- IoT Processing – The collected data is processed by the IoT microcontroller, i.e., Arduino and ESP32.
- Data Transmission – The data is transmitted from the microcontroller to the cloud server through wireless communication networks.
- Cloud Data Storage – The transmitted data is stored in the cloud database for monitoring and analysis purposes.
- AI Data Analysis – The machine data is analyzed by machine learning algorithms for identifying abnormal patterns.
- Fault Detection – If abnormal conditions are detected, i.e., increased vibration and temperature, the system will detect potential failure of the machine.
- Alert Generation – Maintenance alerts are sent to engineers via monitoring dashboards or mobile devices.
- Predictive Maintenance – Maintenance is performed before machine failure, thus avoiding unexpected machine stoppage.

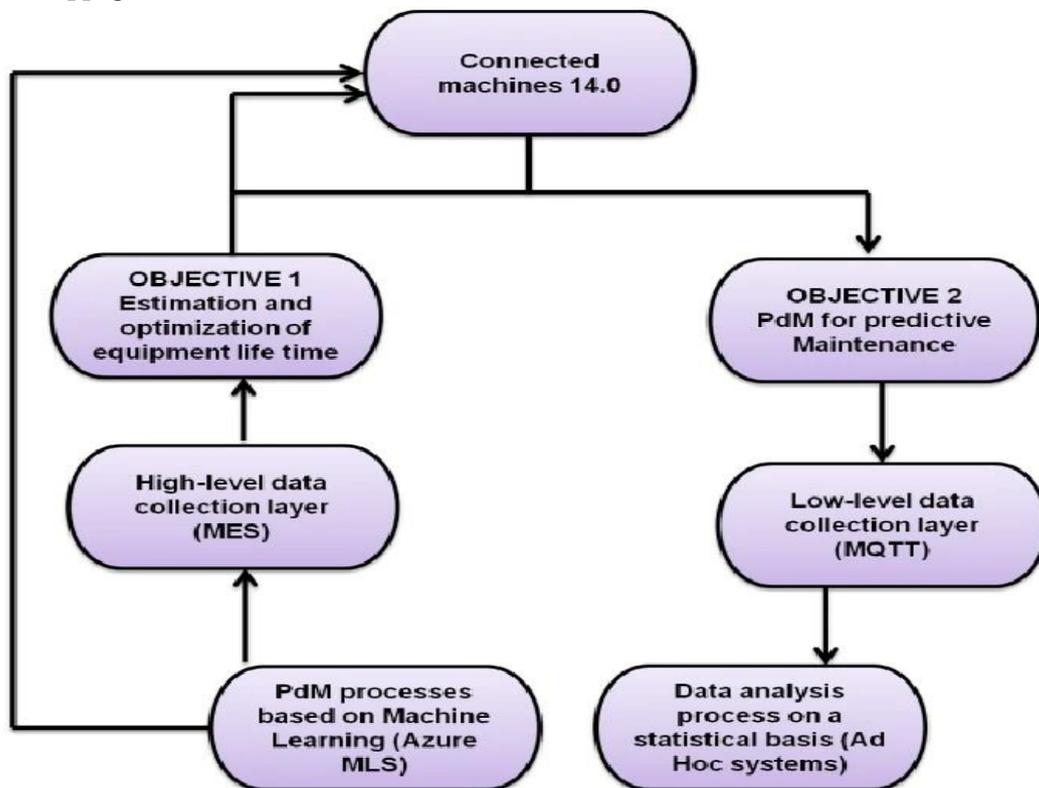
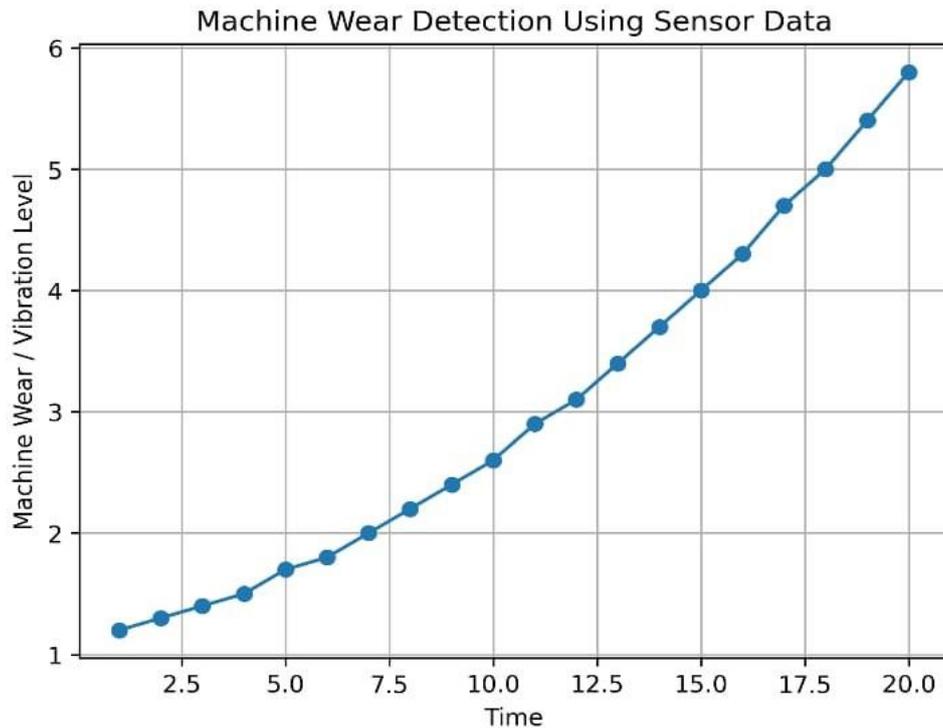


Fig 3: Flowchart of predictive maintenance

Results

The proposed AI and IoT-based predictive maintenance system was implemented with the aim of predicting machine condition and possible faults in industrial machines. Sensors used in the implementation of the proposed system include vibration sensors and temperature and pressure sensors. These sensors were used to collect machine parameters in real time during machine operation [5,2].



Normal operation: 1.0-10.0

Failure zone: 10.00 -20.00

The results of the experimental implementation of the proposed system indicated that the machine parameters were successfully monitored in real time. Under normal machine operation conditions, the machine parameters were within normal limits. However, an increase in the machine vibration level beyond a predetermined threshold was detected as a possible fault in machine operation.

Abnormal temperature rise in the machine was detected as a possible fault in machine operation. Machine learning algorithms were used in the implementation of the proposed predictive maintenance system. These machine learning algorithms were successful in detecting abnormal machine parameters.

As a result, abnormal conditions detected would prompt the system to alert the maintenance engineers through predictive maintenance alerts [4]. This would enable the maintenance engineers to undertake the maintenance activities prior to a serious failure occurring in the machine.

The results of the analysis indicate that the proposed system would be effective in reducing machine downtime, improving the efficiency of maintenance activities, and ensuring the reliability of industrial machines in a modern manufacturing environment.

Discussion

The results of the research in this study show that the integration of Artificial Intelligence (AI) and Internet of Things (IoT) would be effective in improving the efficiency of predictive maintenance activities in industrial machines. The proposed system would monitor machine parameters such as vibration, temperature, and pressure using various sensor technologies [8,5].

The results show that the continuous monitoring of machine status plays a crucial role in the early identification of machine wear and potential faults. For instance, an increase in the level of machine vibration may show signs of bearing failure or machine imbalance. Similarly, a sudden increase in machine temperature

may show signs of machine overheating. By recognizing these abnormal machine states at an early time, maintenance engineers can take necessary steps to prevent machine failure [3,6].

Another significant advantage of the proposed machine maintenance system is the minimization of unexpected machine downtime. Conventional machine maintenance techniques may use predetermined machine maintenance schedules or machine failure. However, the proposed predictive machine maintenance technique allows industries to carry out machine maintenance only during periods of need. This improves machine maintenance efficiency and consequently minimizes machine operation costs [7].

However, machine maintenance systems may face various challenges during implementation, including the high costs of sensor installation and the need for using sophisticated data analysis techniques. Despite these potential challenges in machine maintenance systems, the proposed machine maintenance system using AI and IoT technology presents a promising solution in improving machine reliability and developing smart factories in line with the development of Industry 4.0.

Conclusion

This research presents an AI and IoT based predictive maintenance system for monitoring industrial machines and detecting machine wear at an early stage. The proposed system uses sensors such as vibration, temperature, and pressure sensors to collect real-time data from industrial machines. The collected data is transmitted through IoT communication networks to a cloud platform where it is analyzed using machine learning algorithms.

The results of the study indicate that continuous monitoring of machine parameters helps in identifying abnormal machine behavior and potential faults before a major failure occurs. Early detection of machine problems such as excessive vibration or overheating allows maintenance engineers to take preventive actions and avoid unexpected machine breakdowns. This improves machine reliability and reduces production downtime in industrial environments.

The integration of Artificial Intelligence and Internet of Things technologies provides an intelligent solution for predictive maintenance in modern manufacturing systems. The proposed system can help industries reduce maintenance costs, improve operational efficiency, and support the development of smart factories under the industry 4.0 framework.

Future research can focus on improving data analysis techniques and integrating more advanced machine learning models to enhance the accuracy of fault detection and predictive maintenance systems.

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Shaping the Future of Healthcare with Artificial Intelligence: Innovations and Concerns

Dr. Aakash Singh¹, Dr. Ruby Singh², Dr. Ramesh Kumar Verma³

¹Department of Mechanical Engineering, FoET, DSMNRU, Lucknow, Uttar Pradesh, India

²Assistant Professor, Department of Mechanical Engineering, FoET, DSMNRU, Lucknow, Uttar Pradesh, India

³Assistant Professor, Department of Mechanical Engineering, REC Gonda, Uttar Pradesh, India

ARTICLE INFO

Article History:

Published: 18 March 2026

Publication Issue :

Volume 13, Issue 7
March-April-2026

Page Number :

32-50

ABSTRACT

Artificial Intelligence (AI) is emerging as one of the most transformative forces in modern healthcare, fundamentally reshaping how medical professionals diagnose, treat, and manage illnesses. Rooted in the ability to simulate human cognitive functions such as learning, reasoning, and problem-solving, AI systems leverage vast volumes of structured and unstructured data to recognize patterns, draw insights, and support real-time clinical decision-making. With the exponential growth of digital health data—ranging from electronic health records (EHRs), medical imaging, genetic information, and wearable sensor outputs—AI offers unparalleled opportunities to enhance the accuracy, efficiency, and personalization of healthcare delivery [1].

INTRODUCTION

In clinical diagnostics, AI algorithms can now analyze radiological scans, pathology slides, and genomic sequences with a level of precision that rivals or even exceeds that of human experts. AI-powered predictive models can forecast disease outbreaks, identify patients at risk of complications, and guide preventive care strategies. In therapeutic domains, AI enables the development of personalized medicine, wherein treatments are tailored to the genetic makeup and lifestyle factors of individual patients, improving outcomes and minimizing adverse effects. Robotic-assisted surgeries, virtual health assistants, and AI-driven drug discovery platforms are just a few examples of how this technology is being seamlessly integrated into medical practice [2].

Beyond clinical applications, AI is streamlining administrative and operational processes in healthcare institutions. Automated systems for appointment scheduling, patient triage, billing, and resource allocation are reducing clerical burdens on healthcare staff, thereby improving productivity and allowing professionals to focus more on patient care [3]. In public health, AI models assist in tracking disease progression, evaluating policy interventions, and optimizing healthcare delivery in real-time [4].

Despite its enormous promise, the implementation of AI in healthcare is not without challenges. Ethical concerns around data privacy, informed consent, and algorithmic transparency must be addressed to maintain public trust and protect patient rights [5]. Technical limitations such as biased datasets, lack of generalizability across populations, and the "black box" nature of many AI models hinder full adoption in clinical settings. Regulatory frameworks struggle to keep pace with the rapid development of AI technologies, creating uncertainties regarding validation, approval, and legal liability. Moreover, integrating AI into existing healthcare infrastructure demands significant investments in digital infrastructure, workforce training, and cultural acceptance among healthcare professionals [6].

Therefore, while AI heralds a new era of intelligent and efficient healthcare, its successful integration requires a balanced approach—one that champions innovation while safeguarding ethical standards, ensuring regulatory compliance, and addressing structural and operational challenges. This chapter explores the multifaceted landscape of AI in healthcare, highlighting key innovations, examining the prevailing challenges, and offering insights into the future of this rapidly evolving field.

1. Predictive Analytics and Early Diagnosis

One of the most impactful applications of Artificial Intelligence in healthcare lies in the domain of **predictive analytics and early disease diagnosis**. Leveraging advanced algorithms built on **machine learning (ML)** and **deep learning (DL)** architectures, AI systems are now capable of sifting through massive, complex datasets to identify subtle patterns that may elude even the most experienced clinicians. These datasets include a wide variety of health-related information such as **electronic health records (EHRs)**, **medical imaging**, **genomic data**, and real-time metrics from **wearable devices** and **remote patient monitoring systems**.

Predictive AI tools function by learning from historical patient data to anticipate future health events or outcomes. By recognizing early warning signs and high-risk indicators embedded in patient profiles, these tools empower healthcare providers to intervene proactively, potentially saving lives and reducing the cost of treatment. For example, by analyzing minute changes in vital signs, lab results, or imaging data, AI can flag deteriorating patients long before traditional methods would detect any issues.

A landmark area of progress is **medical imaging**. Deep learning models—particularly convolutional neural networks (CNNs)—have demonstrated remarkable success in diagnosing diseases such as **diabetic retinopathy**, **pneumonia**, **lung cancer**, **tuberculosis**, and **breast cancer** through the analysis of X-rays, MRIs, CT scans, and retinal images. These AI systems have shown diagnostic accuracies comparable to or even exceeding those of trained radiologists in specific tasks, thus offering significant support in clinical settings with limited access to specialists.

In **oncology**, AI-driven image analysis tools are being used not only to detect tumors at their earliest stages but also to **differentiate between malignant and benign growths**, analyze tumor margins, and predict metastatic potential. Similarly, in **cardiology**, AI models can interpret electrocardiograms (ECGs) and echocardiograms to forecast arrhythmias, ischemia, or heart failure before clinical symptoms emerge.

AI is also revolutionizing **predictive risk modeling** in critical care. Tools like the **Epic Sepsis Model** or Google's **DeepMind Health** project analyze a combination of real-time physiological data and patient history to forecast the onset of **sepsis**, **cardiac arrest**, or **respiratory failure** hours before traditional indicators show red flags. Early detection facilitates timely interventions, reducing morbidity and mortality rates significantly.

Wearable devices and Internet of Medical Things (IoMT) technologies further enhance the capabilities of predictive AI. Devices such as smartwatches and biosensors continuously collect data on heart rate, blood

pressure, oxygen saturation, glucose levels, and even stress levels. AI algorithms analyze this stream of information in real-time to detect abnormalities, alert patients and providers, and recommend personalized health strategies. This approach holds particular promise for managing **chronic diseases** like diabetes, hypertension, and chronic obstructive pulmonary disease (COPD), where early intervention can drastically alter disease trajectories.

Moreover, predictive AI is proving useful in **mental health** as well. Natural language processing (NLP) and sentiment analysis tools are being used to examine patient communication patterns—such as tone, word choice, or typing behavior—to flag early signs of **depression**, **anxiety**, or **suicidal ideation**, enabling timely psychological support.

Despite its promise, predictive analytics must be implemented carefully. Accurate prediction relies heavily on **data quality, completeness, and diversity**. Bias in data can result in disparities in prediction accuracy across different population groups. Thus, the development of ethically designed, transparent, and continuously validated AI models is essential to realize the full potential of predictive healthcare.

In summary, AI-enabled predictive analytics and early diagnosis represent a paradigm shift in how medicine is practiced—from a reactive approach to a more proactive, preventive, and personalized model. This transformation not only enhances clinical outcomes but also improves operational efficiency, patient satisfaction, and long-term healthcare sustainability.

2. Personalized Medicine (Expanded)

The emergence of Artificial Intelligence (AI) has significantly accelerated the transition from traditional, one-size-fits-all healthcare models to **personalized medicine**, also known as **precision medicine**. This approach aims to tailor medical treatment and interventions to the individual characteristics of each patient, including their **genetic makeup, lifestyle choices, environmental exposures, and clinical history**. AI acts as the driving force behind this shift by providing the computational power and analytical intelligence needed to interpret complex, high-dimensional biological and clinical data at scale.

A major application of AI in personalized medicine lies in the field of **genomics**. By analyzing genomic sequences, AI algorithms can identify specific **genetic mutations, single nucleotide polymorphisms (SNPs), and biomarkers** that are associated with various diseases, including cancer, cardiovascular disorders, neurological conditions, and rare genetic syndromes. These insights allow for the classification of diseases into molecular subtypes, which in turn enables **targeted therapies** that are far more effective and less toxic than conventional treatments.

For instance, in oncology, AI tools can analyze tumor DNA to detect mutations such as **BRCA1/2, EGFR, HER2, or KRAS**, which inform the selection of therapies like PARP inhibitors or monoclonal antibodies. This means that two patients with the same type of cancer could receive entirely different treatments based on their tumor's genetic signature. AI not only accelerates the identification of actionable mutations but also helps match them with the most appropriate clinical trials or FDA-approved drugs, a process known as **therapy matching**.

In addition to genomics, AI also integrates data from **clinical records, wearable devices, and patient-reported outcomes** to understand an individual's overall health context. For example, AI can analyze dietary habits, physical activity levels, comorbid conditions, and environmental exposures to assess how these factors might influence disease progression or treatment response. This comprehensive view allows clinicians to design **holistic, individualized care plans** that go beyond pharmacotherapy and address broader determinants of health.

Another transformative application is **drug-response prediction**. By using supervised learning models trained on large-scale pharmacogenomic datasets, AI can predict how a specific patient will respond to a given medication. These models take into account variables like liver enzyme activity (e.g., CYP450 metabolism), prior treatment history, allergies, and genetic predispositions to adverse effects. This capability is particularly valuable in managing chronic diseases like depression, epilepsy, and hypertension, where trial-and-error prescribing is common and time-consuming. AI can shorten this trial period significantly, reducing side effects and improving adherence to therapy.

In the realm of **autoimmune diseases and immunotherapy**, AI is being used to develop **immune profiling** tools that predict how a patient's immune system will respond to biologic agents or checkpoint inhibitors. This ensures that only patients likely to benefit are selected for expensive and intensive treatments.

AI also facilitates **real-time treatment adjustment**. Through integration with continuous monitoring tools (e.g., glucose monitors or cardiac implants), AI systems can analyze trends and anomalies in patient data and recommend dose adjustments or lifestyle interventions accordingly. This dynamic approach allows for adaptive care, especially important for diseases like diabetes, where tight glucose control is crucial to preventing complications.

Furthermore, personalized medicine powered by AI holds great promise for **rare diseases**, where patient populations are small and traditional research methods are often impractical. AI can analyze scattered case reports, genomic data, and global registries to identify diagnostic patterns and suggest treatment options, improving outcomes for previously underserved groups.

While the potential of AI in personalized medicine is vast, several challenges remain. Ensuring **data privacy**, **interoperability** among healthcare systems, **transparency in AI decision-making**, and **equitable access** to these technologies are critical to ensuring that all patients benefit from personalized care. Additionally, clinicians must be trained to interpret AI-generated insights responsibly and incorporate them into shared decision-making with patients.

In summary, AI-powered personalized medicine represents a monumental leap forward in the quest for patient-centered care. By aligning treatment strategies with each individual's unique biology and life context, AI enables more effective, safer, and efficient healthcare solutions that improve both patient outcomes and healthcare system performance.

3. Robotics and Surgery

One of the most groundbreaking applications of Artificial Intelligence in modern medicine is in the field of **robotic-assisted surgery**, where AI-powered robotic systems are enhancing surgical precision, improving patient outcomes, and transforming the traditional operating room into a high-tech ecosystem. By combining the dexterity and control of robotics with the analytical and adaptive capabilities of AI, these systems enable surgeons to perform complex procedures with **greater accuracy**, **minimal invasiveness**, and **reduced human error**.

AI-Enhanced Precision and Control

At the core of robotic surgery is the concept of **precision enhancement**. Robotic systems translate a surgeon's hand movements into fine, scaled-down actions that can operate in tight anatomical spaces with minimal disruption to surrounding tissues. AI further augments this by integrating **real-time data processing**, **image-guided navigation**, and **adaptive learning** capabilities into surgical tools. These intelligent systems can

compensate for human hand tremors, track surgical targets with sub-millimeter accuracy, and adjust to intraoperative changes in patient anatomy.

For instance, the **da Vinci Surgical System**—one of the most well-known robotic platforms—uses robotic arms controlled by a surgeon seated at a console. With high-definition 3D visualization and articulating instruments, this system enables precise, minimally invasive procedures in fields such as **urology, gynecology, cardiothoracic surgery, and general surgery**. Patients benefit from **smaller incisions, less pain, reduced blood loss, shorter hospital stays, and faster recovery times** compared to traditional open surgeries.

AI in Autonomous and Semi-Autonomous Surgical Tasks

Beyond assisting surgeons, AI is increasingly enabling **semi-autonomous and autonomous surgical functions**. Algorithms trained on thousands of surgical cases can guide robotic systems to perform **repetitive or high-precision tasks** such as **suturing, tissue dissection, or instrument alignment**. These tasks, though seemingly mechanical, require consistency and accuracy—traits where AI excels. For example, AI-powered robots can perform suturing with standardized tension and spacing, reducing the variability often seen with human hands. One remarkable example is the **Smart Tissue Autonomous Robot (STAR)**, which has demonstrated the ability to suture soft tissue more precisely than human surgeons in controlled environments. This suggests a future where AI could take over routine surgical steps, allowing human surgeons to focus on decision-making and complex maneuvers.

Real-Time Decision Support and Imaging

AI in surgical robotics also plays a crucial role in **intraoperative decision support**. By integrating data from preoperative scans (CT, MRI) with live imaging (ultrasound, endoscopy), AI systems can create real-time **3D maps** of the surgical field. These maps help guide incisions, avoid critical structures like nerves or blood vessels, and suggest optimal pathways for intervention. In neurosurgery and orthopedic surgery, such image-guided systems are invaluable for procedures that demand extreme precision.

Furthermore, AI algorithms can monitor vital signs, blood loss, and tissue response in real time, alerting the surgeon to potential complications or deviations from the surgical plan. This makes the operation safer, particularly in high-risk or emergency cases.

Training and Simulation

AI-powered robotic systems are also revolutionizing **surgical education and training**. Virtual reality (VR) simulators, augmented with AI feedback, allow trainee surgeons to practice in realistic environments, receive performance evaluations, and learn from errors without risking patient safety. These tools can adapt to a trainee's skill level, providing targeted feedback and personalized learning paths. The continuous feedback loop fosters **skill acquisition, confidence-building, and competence** before operating on real patients.

Challenges and Considerations

While robotic and AI-driven surgeries offer immense benefits, several challenges need to be addressed:

- **Cost:** Robotic systems are expensive to acquire and maintain, making them inaccessible to many hospitals, especially in low- and middle-income countries.
- **Training:** Surgeons must undergo specialized training to operate robotic platforms effectively.
- **Regulatory Approval:** Autonomous systems face rigorous testing and regulatory scrutiny to ensure patient safety.
- **Data Privacy:** AI-guided surgical systems collect and store sensitive patient data, requiring robust cybersecurity and ethical safeguards.

4. The Future of AI in Surgery

Looking ahead, AI is expected to play an even greater role in creating **fully autonomous surgical robots**, capable of independently performing entire procedures under human supervision. **Cloud-connected robots** may share data and learn from surgeries performed across the globe, continuously improving their capabilities through federated learning models. Integrating **natural language processing (NLP)** may allow surgeons to issue voice commands to robots during operations, further enhancing ease of use.

In conclusion, AI-powered robotics is transforming surgery from an art reliant on individual skill to a precise, data-driven science. As technology advances, the surgical domain is poised to become more **efficient, standardized, and accessible**, ultimately leading to better patient care and broader global health equity.

Virtual Health Assistants and Chatbots

Artificial Intelligence (AI) is increasingly being deployed in the form of **virtual health assistants** and **chatbots** to enhance patient engagement, improve healthcare accessibility, and reduce the burden on healthcare professionals. These AI-driven tools are designed to simulate human-like conversations and interactions through **natural language processing (NLP)**, **machine learning (ML)**, and **voice recognition technologies**, enabling them to offer 24/7 support to patients across a wide range of health-related tasks.

Round-the-Clock Medical Support

One of the most valuable contributions of AI-powered virtual assistants is the provision of **real-time, round-the-clock support** to patients—regardless of time, location, or resource constraints. These virtual tools can **answer basic medical queries, triage symptoms, and direct patients to appropriate care**, all within seconds. For example, a patient experiencing mild chest discomfort at night can consult a chatbot to receive initial guidance on whether to seek emergency care or wait for a consultation with a physician.

Popular platforms like **Ada Health, Babylon Health, and Your.MD** are already delivering such services worldwide, offering interactive symptom checkers that analyze user inputs and generate preliminary health assessments or suggestions for next steps. These systems are continually improving through feedback loops and integration with up-to-date medical knowledge bases.

Chronic Disease Management

Virtual health assistants play a particularly vital role in the **monitoring and management of chronic conditions** such as diabetes, hypertension, asthma, and heart disease. These assistants can collect data from connected wearable devices and home monitoring tools, analyze patterns in patient health metrics, and provide personalized feedback. For instance:

- A diabetic patient might receive alerts about abnormal glucose levels and dietary tips.
- A hypertensive patient could be reminded to measure blood pressure and adhere to prescribed lifestyle modifications.

Advanced AI assistants can also escalate concerns to human healthcare providers when they detect anomalies or signs of deterioration, enabling **timely intervention** and **reducing hospital readmissions**.

Medication and Appointment Reminders

A significant challenge in healthcare is **non-adherence to medication and appointments**, which can compromise treatment outcomes and increase healthcare costs. Virtual health assistants are being programmed to serve as **digital caregivers**, sending **customized reminders** to patients to:

- Take medications at scheduled times.
- Refill prescriptions.

- Attend upcoming medical appointments or follow-ups.
- Track side effects and medication responses.

These features not only improve compliance but also empower patients to take a more active role in their care.

Mental Health and Emotional Support

Beyond physical health, AI chatbots are also being developed to offer **mental health support**. Tools like **Woebot** and **Wysa** engage users in cognitive behavioral therapy (CBT)-based conversations to help them cope with stress, anxiety, or depression. While not a replacement for licensed therapists, such tools can serve as **first-line support systems** or complements to professional care, especially for individuals in remote or underserved areas. These systems provide **anonymity**, **non-judgmental interactions**, and **instant availability**, which may encourage individuals who are hesitant to seek traditional mental health care to take the first step.

Administrative Efficiency and Triage

In clinical settings, chatbots and virtual assistants reduce administrative burdens by **handling routine queries** such as insurance information, clinic hours, test result notifications, and paperwork guidance. More advanced systems can also perform **triage functions**, helping healthcare institutions prioritize cases based on severity and direct patients to the most appropriate departments.

For example, during pandemics or public health emergencies, AI chatbots have been used to:

- Screen users for symptoms.
- Provide information on testing and isolation guidelines.
- Reduce patient load on hotlines and emergency services.

Personalized Health Coaching

With the integration of AI and behavioral science, virtual assistants can act as **personalized health coaches**, helping users set goals for weight loss, sleep improvement, smoking cessation, or physical fitness. These assistants adapt their coaching style based on user interaction patterns, preferences, and progress, making them more engaging and effective than generic health apps.

Challenges and Ethical Considerations

Despite their growing popularity, virtual health assistants and chatbots face several challenges:

- **Accuracy:** Inaccurate or outdated medical advice can pose risks to patient safety.
- **Data Security:** Storing and processing sensitive health information must be done under stringent data protection standards (e.g., HIPAA, GDPR).
- **Empathy and Trust:** AI lacks true empathy, which may limit its effectiveness in emotionally sensitive situations.
- **Accessibility and Language Diversity:** Systems must be inclusive, offering support in multiple languages and formats (text, voice) for people with disabilities.

The Road Ahead

As AI technology advances, virtual assistants are expected to become even more intelligent, conversationally fluent, and emotionally responsive through developments in **natural language understanding (NLU)**, **voice synthesis**, and **emotion recognition**. They are likely to be integrated seamlessly into electronic health records, telehealth platforms, and smart home devices, creating a **continuous, personalized care ecosystem**.

In summary, AI-powered virtual health assistants and chatbots represent a **cost-effective, scalable, and accessible** solution to support patients and healthcare systems in an increasingly digital world. Their ability to

bridge gaps in care, especially in underserved or overstretched environments, makes them a vital component of the future of healthcare delivery.

5. Administrative and Operational Efficiency

While much of the attention around Artificial Intelligence (AI) in healthcare is focused on diagnostics and treatment, one of its most immediate and impactful applications lies in **streamlining administrative and operational processes**. Healthcare systems worldwide are burdened by **rising costs, staff shortages, and administrative overload**—issues that not only strain healthcare workers but also compromise patient care. AI technologies, particularly those involving **natural language processing (NLP)**, **robotic process automation (RPA)**, and **machine learning (ML)**, are increasingly being adopted to reduce manual tasks, enhance productivity, and optimize institutional workflows.

Automated Medical Coding and Billing

A major administrative challenge in healthcare is **medical coding**, which involves translating physician notes, diagnoses, and procedures into standardized codes (like ICD-10 or CPT codes) for billing and insurance reimbursement. Traditionally performed by trained coders, this process is time-consuming, prone to human error, and often results in **delays or inaccuracies** that affect hospital revenues and patient satisfaction.

AI-enabled coding systems can analyze **clinical documentation** using NLP algorithms to extract relevant medical terms, interpret context, and assign accurate billing codes automatically. These tools not only **increase coding speed and accuracy** but also reduce the risk of compliance violations and claim denials. For example, platforms like **3M's CodeFinder™** or **Cerner's AI-driven solutions** are helping health systems automate this complex task, improving both efficiency and financial outcomes.

Appointment Scheduling and Patient Engagement

Efficient scheduling is crucial for reducing patient wait times, improving provider utilization, and avoiding appointment no-shows. AI-powered scheduling tools can dynamically assess factors such as physician availability, patient preferences, and clinical urgency to **optimize appointment slots**. These systems also offer **self-service portals** where patients can book or reschedule appointments with ease, receive automated reminders, and reduce dependency on front-desk staff.

Advanced AI systems can even **predict cancellations and no-shows** using historical data and patient behavior patterns, allowing facilities to implement overbooking strategies or outreach efforts to fill gaps. For instance, predictive analytics may flag a patient with a history of missed appointments and trigger a follow-up call or rescheduling suggestion.

Optimizing Patient Flow and Hospital Resource Management

One of the most complex challenges hospitals face is **managing patient flow**—ensuring that patients move smoothly through admission, diagnosis, treatment, and discharge without delays or bottlenecks. AI algorithms can analyze **real-time data** from emergency departments, surgical suites, intensive care units (ICUs), and inpatient wards to predict **bed availability, length of stay, and discharge times**.

This enables administrators to:

- **Optimize bed utilization.**
- **Reduce overcrowding in emergency rooms.**
- **Schedule elective surgeries without disrupting urgent care.**
- **Allocate staff and equipment efficiently.**

For example, AI tools like **GE Healthcare's Command Center** or **Qventus** use real-time dashboards and predictive analytics to help hospital administrators make informed operational decisions and allocate resources proactively.

Workflow Automation and Documentation Support

Physicians and nurses spend a significant portion of their time on **clinical documentation**, data entry, and report generation. AI-powered transcription tools and **virtual scribes** can listen to doctor-patient interactions, convert speech to structured text, and automatically update electronic health records (EHRs). This dramatically reduces clerical workload, allowing clinicians to focus more on patient care.

Technologies like **Dragon Medical One** or **Suki AI** are revolutionizing this space by using speech recognition and contextual understanding to **generate clinical notes, orders, and referrals** in real-time. This improves **workflow efficiency**, reduces burnout, and enhances documentation accuracy.

Inventory and Supply Chain Optimization

Hospitals often face challenges in managing medical supplies, pharmaceuticals, and equipment inventory. AI-based inventory management systems can forecast demand based on usage patterns, seasonal trends, and patient volume. This ensures **adequate stock levels**, prevents **shortages**, and reduces **wastage due to overstocking or expiration**.

AI can also track supply chain disruptions, automate purchase orders, and negotiate vendor contracts through intelligent procurement systems, creating more resilient and cost-effective hospital operations.

Cost Reduction and Financial Optimization

AI is instrumental in helping healthcare institutions control costs. Predictive analytics can model financial risk, identify areas of overspending, and suggest cost-saving measures. Fraud detection algorithms can also monitor billing patterns and claims to identify suspicious activity, preventing revenue losses due to **insurance fraud or duplicate billing**.

Additionally, AI assists in **revenue cycle management** by forecasting cash flows, optimizing charge capture, and reducing claim denials—resulting in improved financial sustainability for healthcare providers.

Challenges in AI-Driven Administration

Despite its benefits, the implementation of AI in administrative operations is not without hurdles:

- **Integration with legacy systems** can be complex and costly.
- **Staff training and acceptance** are crucial to avoid resistance to AI tools.
- **Data quality and interoperability** remain significant issues in many healthcare settings.
- **Ethical considerations** must be addressed when automating tasks involving patient interaction or data handling.

The Future Outlook

As AI continues to evolve, its role in healthcare administration is expected to expand further with the help of:

- **Conversational AI** to replace traditional call centers.
- **Digital twins of hospitals** to simulate operations and forecast performance.
- **AI-driven decision support** for strategic planning and workforce management.

In conclusion, AI's contribution to administrative and operational efficiency is helping healthcare institutions **optimize resources, reduce costs, streamline workflows, and enhance patient satisfaction**. While clinical advancements often steal the spotlight, it is the transformation of backend operations through AI that may prove most critical in sustaining healthcare systems over the long term.

6. Drug Discovery and Development

Drug discovery is one of the most **time-consuming, resource-intensive, and costly** processes in healthcare, often taking over a decade and billions of dollars to bring a single drug from laboratory to market. Traditional methods involve a laborious cycle of compound screening, target identification, preclinical testing, and clinical trials—many of which fail at various stages. However, Artificial Intelligence (AI) is rapidly transforming this landscape by **streamlining discovery, optimizing compound selection, and enhancing clinical trial design**, thereby accelerating the pace of innovation and improving the likelihood of success.

Analyzing Chemical Interactions and Target Prediction

At the earliest stages of drug development, AI algorithms are used to **analyze the interactions between chemical compounds and biological targets**, such as proteins, enzymes, or DNA. Using deep learning, graph neural networks, and molecular modeling, AI can predict **how a molecule will bind to a specific target**, estimate its **binding affinity**, and assess **its toxicity or side effects**—all in silico (via computer simulation) before lab testing even begins.

For instance, AI systems can process millions of molecular structures in databases and identify **patterns associated with therapeutic efficacy or toxicity**. This allows researchers to prioritize the most promising compounds for synthesis and testing, significantly **reducing the time and cost associated with random trial-and-error approaches**.

Companies like **Atomwise** and **Insilico Medicine** use AI to simulate chemical interactions at the atomic level, identifying leads that would be difficult or impossible to find using conventional screening techniques.

Identification of Novel Drug Candidates

AI excels at **de novo drug design**, where algorithms generate entirely new molecular structures based on the desired properties of a drug—such as solubility, bioavailability, and minimal side effects. By training on existing datasets of known drugs, AI models can **propose novel compounds** that are chemically viable and optimized for specific targets.

These tools not only speed up the **identification of drug candidates** but also enable researchers to **repurpose existing drugs** for new indications, a strategy known as **drug repositioning**. For example, during the COVID-19 pandemic, AI was instrumental in rapidly identifying existing drugs that could potentially treat the virus, helping to inform emergency treatment protocols.

Preclinical Testing and Toxicity Prediction

Before a drug reaches human trials, it must undergo rigorous preclinical testing to assess its safety in animal models. AI is now being used to simulate these stages using **computational biology models**, reducing the reliance on animal testing. Tools like **in silico toxicity prediction** models analyze chemical structures and historical toxicology data to forecast how a drug will behave in the human body.

This **virtual screening** process enables the early elimination of potentially harmful compounds, conserving resources and improving the ethical profile of the research.

Accelerating and Optimizing Clinical Trials

Clinical trials are notoriously slow and expensive, often accounting for more than half of a drug's total development cost. AI contributes to **optimizing clinical trial design** in several ways:

- **Patient selection and recruitment:** AI can analyze EHRs, genetic data, and social determinants of health to identify eligible participants with specific biomarkers or disease subtypes.

- **Site selection and trial feasibility:** Machine learning models help sponsors choose trial locations where patient populations, infrastructure, and regulatory compliance align with study goals.
- **Monitoring and adaptive design:** AI-powered tools monitor trial data in real-time, detecting adverse events, adjusting dosages, and recommending design changes to improve trial outcomes.

By reducing **trial dropout rates**, enhancing **participant diversity**, and enabling **faster decision-making**, AI makes clinical trials more efficient and inclusive.

Personalized Drug Development

AI also plays a role in the emerging field of **personalized pharmacology**, where medications are designed or adapted based on an individual's **genomic profile**, **microbiome composition**, or **immune status**. This is particularly relevant for therapies such as **cancer immunotherapy**, where a drug's success may depend on highly individualized factors.

AI can analyze a patient's specific biological data to suggest optimal drug regimens, predict treatment responses, and avoid adverse effects, thus increasing the likelihood of therapeutic success.

Success Stories and Industry Adoption

Several successful examples highlight AI's growing role in pharmaceutical innovation:

- **Exscientia**, an AI-driven drug design company, partnered with Sumitomo Dainippon Pharma to develop the first fully AI-designed molecule (DSP-1181) to enter human trials for obsessive-compulsive disorder.
- **DeepMind's AlphaFold** revolutionized structural biology by predicting the 3D structure of proteins with near-laboratory accuracy, a breakthrough that will greatly accelerate target identification and drug design.

Pharmaceutical giants like **Pfizer**, **Novartis**, and **Roche** have invested heavily in AI partnerships and platforms to drive innovation across their research pipelines.

Challenges in AI-Driven Drug Discovery

Despite its promise, AI in drug discovery is not without obstacles:

- **Data quality and standardization:** Biological data is often noisy, incomplete, or inconsistent across sources.
- **Interpretability:** Many AI models function as "black boxes," making it difficult for scientists to understand how decisions are made.
- **Regulatory hurdles:** Drug regulators like the FDA and EMA are still developing frameworks for evaluating AI-designed drugs and virtual trials.
- **Ethical concerns:** Issues around patient data privacy, algorithmic bias, and the exclusion of underserved populations must be addressed to ensure equitable outcomes.

The Future of AI in Pharmaceutical R&D

As computational power increases and AI models become more sophisticated, the future of drug discovery looks poised for exponential growth. With **cloud computing**, **federated learning**, and **integrated omics data (genomics, proteomics, metabolomics)**, AI will continue to unlock deeper insights into disease mechanisms and treatment strategies. The integration of AI into **digital twin models**—virtual replicas of individual patients—may soon allow for real-time drug testing and optimization without the need for actual exposure.

In summary, AI is revolutionizing drug discovery and development by making it faster, cheaper, safer, and more precise. From molecular design to clinical validation, AI is not just accelerating the process but also redefining what is possible in the realm of pharmaceutical science.

Challenges and Limitations of AI in Healthcare

While Artificial Intelligence (AI) holds immense promise in transforming the healthcare industry, its implementation is not without significant challenges. These hurdles span technological, ethical, legal, and operational domains. Understanding and addressing these limitations is essential to harness AI's full potential responsibly and equitably.

1. Data Privacy and Security

AI systems in healthcare depend heavily on vast volumes of sensitive and personal data—including electronic health records (EHRs), genomic sequences, medical imaging, and real-time biometric monitoring. This reliance raises critical concerns around **data privacy, patient consent, and information security**.

a. Vulnerability to Cyberattacks and Data Breaches

Medical data is among the most sensitive categories of personal information and is increasingly targeted by cybercriminals due to its value on the black market. AI systems, especially those operating on cloud-based infrastructures or integrating Internet of Medical Things (IoMT) devices, may present multiple points of vulnerability. A data breach could expose patient identities, diagnoses, treatment histories, and even insurance or financial information.

b. Regulatory Compliance

Compliance with global and regional privacy regulations is a significant barrier:

- **HIPAA (Health Insurance Portability and Accountability Act)** in the U.S. mandates strict safeguards for Protected Health Information (PHI).
- **GDPR (General Data Protection Regulation)** in the EU includes provisions like data minimization, consent, and the right to be forgotten, all of which are challenging for AI systems that require large, persistent datasets for training.
- India's **Digital Personal Data Protection Act (DPDP)** also emphasizes informed consent, limited data processing, and data fiduciary responsibilities.

Ensuring that AI applications adhere to these complex legal frameworks requires **continuous legal review, data governance audits, and privacy-by-design approaches**.

c. Need for Cybersecurity Infrastructure

Healthcare organizations often lack robust cybersecurity infrastructures. Without end-to-end encryption, intrusion detection systems, and secure APIs, AI platforms become high-risk. Implementing **multi-layered data security** strategies, including federated learning (which avoids centralized data storage), zero-trust architectures, and real-time monitoring, is vital to protect sensitive medical data.

2. Bias and Fairness

One of the most widely discussed challenges of AI in healthcare is **algorithmic bias**, which can lead to inaccurate diagnoses, unequal treatment recommendations, and systemic discrimination, particularly against already marginalized populations.

a. Bias in Training Data

AI models are only as good as the data on which they are trained. If datasets predominantly represent certain populations (e.g., white males in North America), the model's predictive performance may be poor or harmful for others, such as women, people of color, children, or those with rare conditions.

A study by *Nature* found that some skin cancer detection algorithms performed significantly worse on darker skin tones, as the datasets lacked diverse representation. Similarly, an algorithm used in U.S. hospitals was found to underestimate the healthcare needs of Black patients because it used past healthcare costs as a proxy for health status—ignoring disparities in healthcare access.

b. Perpetuation of Health Disparities

When biases in data or algorithm design go unchecked, AI systems can reinforce existing health disparities:

- Patients from underserved communities may be deprioritized in predictive models.
- Language models may fail to interpret non-standard dialects or local expressions of symptoms.
- Certain diseases prevalent in developing regions may be underrepresented in global datasets, leading to limited diagnostic accuracy.

This not only undermines **clinical effectiveness** but also erodes **patient trust** in AI-enabled care.

c. Ethical AI Development

Mitigating bias requires a conscious, ethical approach to AI development:

- **Diverse and representative datasets** must be used during training and validation stages.
- **Fairness audits and algorithmic transparency** should be integrated into the AI lifecycle.
- **Explainable AI (XAI)** methods must be employed to ensure clinicians and regulators understand how decisions are made.

Developers must also consider **intersectional factors**—how gender, age, socioeconomic status, and geography interact to impact patient outcomes—rather than treating populations as homogenous units.

d. Lack of Regulatory Standards for Bias

Currently, there is no global standard for measuring and regulating bias in healthcare AI. Efforts are underway to establish frameworks—such as the **World Health Organization’s Guidance on Ethical AI**—but these are yet to be universally adopted or enforced.

3. Lack of Explainability (The Black Box Problem)

One of the foremost limitations of AI in healthcare is the issue of **lack of explainability**, often referred to as the “**black box problem**.” Many high-performing AI models, especially those based on **deep learning algorithms**, are capable of generating remarkably accurate predictions. However, these models function through complex, multi-layered computations that are not easily interpretable by humans—even by the developers themselves.

This lack of transparency raises serious concerns in a healthcare setting, where **clinical decisions must be justified** to both medical professionals and patients. Physicians are trained to understand, question, and explain the rationale behind any diagnosis or treatment plan. When an AI system provides a result—such as identifying a malignant tumor from an imaging scan—without a clear reasoning path, it creates **ambiguity and hesitation**.

The inability to interpret AI decisions impacts several aspects of healthcare delivery:

- **Clinical Trust:** Physicians may be reluctant to rely on AI systems if they cannot verify or understand the reasoning behind the predictions.
- **Patient Communication:** Informed consent and shared decision-making are critical components of ethical healthcare. Patients may lose confidence in their care if decisions are based on opaque algorithms.
- **Medical Accountability:** In case of adverse outcomes, it becomes difficult to assign responsibility when AI tools are involved but their decisions are not explainable.

In response to these concerns, the field of **Explainable Artificial Intelligence (XAI)** has emerged. XAI seeks to develop AI models that provide interpretable, transparent, and trustworthy outputs. Techniques such as **SHAP (SHapley Additive exPlanations)** and **LIME (Local Interpretable Model-agnostic Explanations)** attempt to highlight which data features influenced a particular decision. Furthermore, **visual tools** are being developed to help clinicians understand the focus areas in medical images processed by AI.

Despite these advances, XAI remains in its nascent stage. A balance must be struck between **model accuracy and interpretability** to ensure that AI tools are both powerful and usable in real-world clinical environments.

4. Regulatory and Legal Hurdles

Another significant challenge in the implementation of AI in healthcare is the **complexity of regulatory and legal frameworks**. The healthcare sector is highly regulated to ensure patient safety, uphold medical ethics, and maintain public trust. The introduction of AI-based technologies—ranging from diagnostic software to robotic surgical tools—adds a new layer of complexity to this regulatory environment.

a. Lack of Standardized Regulatory Frameworks

Currently, **regulatory bodies** such as the **U.S. Food and Drug Administration (FDA)**, **European Medicines Agency (EMA)**, and **India's Central Drugs Standard Control Organization (CDSCO)** are still in the process of formulating comprehensive guidelines specifically tailored for AI-driven healthcare technologies. Most existing regulations are designed for traditional medical devices or pharmaceuticals and are not equipped to handle:

- The **adaptive nature** of AI systems, which can evolve through continuous learning.
- The **dynamic data inputs** that influence AI outputs in real-time.
- The **hybrid integration** of software, data, and devices in modern AI tools.

This lack of clear regulatory pathways creates **delays in product approvals**, discourages innovation, and makes it difficult for healthcare institutions to adopt AI-based solutions with confidence.

b. Legal Accountability and Liability

The use of AI also raises critical questions regarding **legal accountability**. In conventional medical practice, liability for misdiagnosis or treatment errors is typically assigned to the treating physician or hospital. However, in cases where AI contributes significantly to clinical decision-making, it is unclear who should bear the responsibility if the AI system:

- Fails to detect a serious condition.
- Recommends an incorrect treatment.
- Malfunctions due to technical faults.

These grey areas in **medical liability law** can create legal disputes involving software developers, hospitals, physicians, and insurance providers. Until robust legal frameworks are developed to address such scenarios, healthcare providers may be reluctant to fully integrate AI into critical workflows.

c. Ethical and Consent Issues

Another regulatory challenge is ensuring **ethical compliance**, especially in relation to patient consent and data governance. Patients must be made aware when AI is used in their diagnosis or treatment. Informed consent must include:

- The **role of AI** in the clinical process.
- The **limitations and risks** associated with algorithmic decision-making.
- The **fallback procedures** in case of AI malfunction or error.

Moreover, international regulations such as the **General Data Protection Regulation (GDPR)** and the **Health Insurance Portability and Accountability Act (HIPAA)** require stringent data handling, encryption, and transparency measures. AI systems, which rely on massive datasets to function, must therefore incorporate **privacy-by-design principles** to ensure legal and ethical compliance.

5. Integration into Clinical Workflows

While Artificial Intelligence (AI) offers transformative potential in enhancing diagnostic accuracy, streamlining operations, and personalizing treatment, its **seamless integration into real-world clinical workflows** remains a significant challenge. Clinical settings operate within tightly coordinated routines, and any disruption to this ecosystem can lead to inefficiencies, resistance, or even patient risk. Despite the growing number of AI-based tools being developed and deployed, many healthcare institutions and professionals have been slow or hesitant to adopt them fully into daily practice.

a. Lack of Training and Familiarity

Most healthcare professionals—physicians, nurses, technicians—are trained in traditional biomedical sciences and **lack formal education or experience with AI systems**. The introduction of AI-based diagnostic platforms, decision-support systems, and automated documentation tools often requires a **steep learning curve**, which may deter already overburdened clinicians from engaging with these technologies. Without **structured training programs** and continuous professional development in AI literacy, many clinicians remain skeptical or unprepared to adopt such tools.

b. Workflow Disruptions

AI tools are often developed in isolation from the actual clinical environment, resulting in solutions that may not align with the **real-time demands, timing, or structure** of hospital workflows. For example, if an AI-based diagnostic system produces recommendations that arrive after a treatment decision has already been made, its utility becomes questionable. Similarly, tools that require excessive data input, new protocols, or separate interfaces may **slow down processes** rather than improving them. For AI to be effective, it must **integrate smoothly with existing Electronic Health Record (EHR) systems**, support clinician workflows, and provide **real-time, actionable outputs**.

c. Human-Machine Relationship Concerns

There are also **psychosocial and professional concerns** among clinicians regarding the growing use of AI in healthcare. Some practitioners fear that AI may eventually **replace human judgment** or reduce the value of their expertise. Others worry about **over-reliance on automated systems**, which could lead to skill erosion or complacency. These apprehensions are especially relevant in sensitive tasks like diagnosis, prognosis, or surgical planning, where **clinical experience and contextual judgment** remain irreplaceable.

To address these concerns, AI systems must be designed not as replacements, but as **assistive tools** that empower clinicians, enhance accuracy, and reduce cognitive burden. Emphasizing a **collaborative model of decision-making**—where AI augments human insight—can help in building trust and ensuring successful integration into clinical workflows.

6. Infrastructure and Cost Barriers

The successful deployment of AI in healthcare depends heavily on the **availability of supportive infrastructure and sufficient financial investment**. In many regions, especially low- and middle-income countries, the **lack of foundational resources** presents a formidable barrier to AI adoption. These constraints limit not only the ability to implement AI tools but also the sustainability and scalability of such innovations.

a. Need for High-Quality Digitized Data

AI systems, particularly those based on machine learning, require access to **large volumes of accurate, well-annotated, and digitized medical data**, such as imaging studies, patient records, lab results, and genetic profiles. In many healthcare institutions, especially in rural or underfunded settings, medical records are still maintained in **paper formats** or fragmented digital systems, making them unsuitable for AI training and deployment. The lack of **standardized data formats**, poor data interoperability, and inconsistent data quality further impede the development and use of effective AI tools.

b. Investment in Computational Infrastructure

Advanced AI models require **robust computational infrastructure**, including high-speed processors, secure data storage systems, cloud computing platforms, and reliable internet connectivity. Maintaining such infrastructure involves **substantial upfront capital investment** and recurring operational costs. Many public hospitals, community clinics, and small private practices, especially in resource-poor regions, may not possess the financial capacity or technical expertise to establish and maintain this level of infrastructure.

c. Shortage of Skilled Personnel

Another major constraint is the shortage of **skilled technical personnel**, such as data scientists, AI engineers, clinical informaticians, and cybersecurity experts, who are essential for the **implementation, customization, and maintenance** of AI systems in healthcare settings. Even when AI tools are available, the absence of trained human capital often leads to underutilization or inefficient deployment.

While Artificial Intelligence holds immense promise for revolutionizing healthcare delivery, its widespread adoption faces a host of **challenges and limitations** that must be systematically addressed. These obstacles span across **technological, ethical, infrastructural, regulatory, and human domains**, highlighting the complexity of integrating AI into real-world clinical practice.

One of the foremost concerns is **data privacy and security**. AI systems thrive on vast quantities of sensitive patient data, making them potential targets for cyberattacks and privacy breaches. Ensuring compliance with global and national data protection regulations—such as GDPR and HIPAA—is imperative to maintain trust and safeguard personal health information.

Closely tied to this is the issue of **bias and fairness**. If AI models are trained on non-representative datasets, they risk reinforcing existing health disparities and delivering unequal care. Ethical AI development must be rooted in diversity, inclusivity, and transparency to ensure equitable outcomes for all patient populations.

Another major limitation is the **lack of explainability** in many AI systems, especially those based on deep learning. Known as the "black box" problem, this lack of interpretability undermines clinician trust and limits accountability. Promoting the development of **explainable AI (XAI)** tools is critical to ensure informed and defensible decision-making in clinical settings.

Further complicating adoption are the **regulatory and legal uncertainties** surrounding AI in healthcare. Regulatory bodies are still evolving frameworks to evaluate and approve AI tools, while legal accountability for AI-related errors remains ambiguous. A clear, adaptive, and internationally harmonized regulatory landscape is essential for safe and effective integration.

On the operational front, AI often faces resistance in **clinical workflows** due to disruptions, lack of AI literacy among clinicians, and fears of professional displacement. Successful implementation depends on fostering a collaborative human-AI interface and embedding AI into healthcare processes in a user-friendly, non-intrusive manner.

Infrastructure and cost barriers present additional hurdles, particularly in low-resource settings. The lack of digitized data, inadequate computational infrastructure, and shortage of skilled personnel severely restrict the scalability of AI solutions. Bridging these gaps will require strategic investments, policy support, and cross-sector collaboration.

To overcome these challenges, a **multi-pronged approach** is necessary. This includes increasing investments in healthcare digitization, promoting public-private partnerships for infrastructure development, and launching national-level training programs in **AI and health informatics**. Without adequate resources, the benefits of AI in healthcare will remain limited to well-funded, urban, or private institutions, thus exacerbating the **digital divide** and health inequities.

While AI in healthcare is a rapidly advancing frontier with transformative potential, its true success depends on our ability to **responsibly, ethically, and equitably overcome these multifaceted challenges**. Building a supportive ecosystem—encompassing robust data governance, fair algorithm design, clinician training, regulatory clarity, and infrastructure development—is essential for unlocking the full promise of AI and ensuring that its benefits are **accessible to all**, regardless of geography, socioeconomic status, or medical condition.

Ethical Considerations in AI-Driven Healthcare

The integration of Artificial Intelligence into healthcare systems brings about not only technological and clinical transformation but also significant **ethical implications**. As AI becomes increasingly involved in diagnosis, treatment, and patient management, it is vital to uphold **core ethical principles** that safeguard human dignity, trust, and autonomy. The following ethical dimensions are central to the responsible use of AI in healthcare:

1. Informed Consent

One of the cornerstones of medical ethics is the **principle of informed consent**, which becomes increasingly complex in the context of AI-driven healthcare. Patients have the right to know when artificial intelligence tools are being used in their diagnosis or treatment. This includes clear communication regarding:

- The **role of AI** in the medical decision-making process.
- The **extent to which AI systems influence or determine outcomes**.
- Potential **risks, benefits, and limitations** of AI recommendations.

Obtaining informed consent in AI-assisted care settings requires adapting traditional consent procedures to include explanations of algorithmic functions in **patient-friendly language**.

2. Transparency and Accountability

AI models, particularly those based on deep learning, often operate as "**black boxes**", providing results without easily understandable reasoning. This lack of **transparency** can erode both clinician and patient trust. Ethically, it is essential to:

- Ensure that healthcare providers can **interpret and explain** AI-generated recommendations.
- Disclose **how data is used**, how models are trained, and **how decisions are derived**.
- Develop **explainable AI (XAI)** models that prioritize interpretability alongside performance.

In addition, the question of **accountability** remains paramount—if an AI system causes harm, it must be clear who is legally and morally responsible: the developer, the healthcare provider, or the institution.

3. *Autonomy and Trust*

AI should function as a **supportive tool** that enhances clinical decision-making rather than replacing the human touch essential to medicine. Preserving **patient autonomy** means:

- Empowering individuals to participate actively in decisions affecting their health.
- Ensuring that final clinical decisions are made or approved by **qualified human professionals**, not algorithms alone.
- Promoting **trust** by involving patients in the process and respecting their preferences and values.

Trust is not only built on transparency and autonomy, but also on the assurance that **AI systems are reliable, safe, and ethically designed**. Upholding these ethical norms is crucial to fostering a healthcare environment where innovation coexists with empathy, equity, and respect.

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Study on Thermal Magneto-Resistive Heat Switches

Aman Shakya¹, Dr. Rakesh Verma², Toofan Singh³

¹Department of Mechanical Engineering ,FoET, DSMNRU, Lucknow, U.P (INDIA)

²Assistant Professor, Department of Mechanical Engineering, FoET, DSMNRU, Lucknow, U.P (INDIA)

³Assistant Professor, Department of GITI,Nawabganj,Barabanki.

ARTICLE INFO

Article History:

Published: 18 March 2026

Publication Issue :

Volume 13, Issue 7

March-April-2026

Page Number :

51-57

ABSTRACT

The need for continuous sub-Kelvin cooling in spaceborne observatories and quantum processing units has led to the development of solid-state heat switches with reliability, high switching ratios, and fast switching speeds. This research presents a comprehensive comparative analysis of existing heat switch technology, including mechanical heat switches, gas gap heat switches, and thermo-magneto-electric generator systems. It also presents a new method of developing magnetoresistive heat switches (MRHS) using single-crystal tungsten material. A new methodology of combining geometrical optimization with a specific orientation of the magnetic field of 90 degrees is discussed. This new methodology eliminates the disadvantages of inhomogeneity of the magnetic field and low switching ratios reported in the foundational research. Experimental and analytical results show a new standard of a switching ratio of 36,822 at a temperature of 0.5 K and a magnetic field of 3 T using an optimized cross-section area of 2.25 mm² with a perpendicular magnetic field penetration. These results show a new standard of more than 100% over existing heat switches in the development of adiabatic demagnetization refrigerators. Research gaps in the areas of magnet system masses, magnetic fields, and manufacturing complexities are discussed.

INTRODUCTION

The requirement for temperature levels below 1 Kelvin is vital for the proper functioning and maintenance of various scientific instruments, from superconducting transition-edge sensors to large arrays of bolometers for the mapping of cosmic microwave background radiation[1] . In these environments, it is vital to reduce thermal noise levels to a minimum in order to detect weak signals. Although dilution refrigerators have been the backbone of laboratory refrigeration, the requirement for gravity and the management of helium-3/helium-4 mixtures make them unsuitable for the stringent demands required for space research[2]. Therefore, Adiabatic Demagnetization Refrigerators have come to be recognized as the best option for space research in the field of sub-Kelvin refrigeration.[3][4]

The operational efficiency of an ADR is, in fact, critically dependent on the heat switches, which are used to control the heat transfer between the paramagnetic salt pill and the heat sink. During the magnetization process, the heat switch has to be in the "ON" state, i.e., have high thermal conductance, in order to remove the heat of magnetization. On the other hand, during the demagnetization process, it has to be in the "OFF" state, i.e., have perfect thermal insulation, in order not to leak any heat into the cold stage[1]. The efficiency of these heat switches is, in fact, quantified in terms of the so-called "switching ratio" (Sr), defined as the ratio of thermal conductivity in the "ON" state and that in the "OFF" state.[1][5]

However, traditional heat switches are plagued by reliability and switching time issues. While mechanical switches are prone to failure due to moving parts or cold-welding in a vacuum environment, gas gap switches are limited by the slow adsorption/desorption rate of the exchange gas[1]. Magnetoresistive heat switches (MRHS), which exploit the large thermal conductivity change of compensated metals under a magnetic field, provide a new class of heat switches that are free from moving parts and are limited only by the rate at which the magnetic field is applied[6]. Tungsten (W) is a leading candidate for MRHS devices due to its extremely low superconducting transition temperature (T_c - approx - 0.015K) and its high Debye temperature (Θ_D approx -310 K), which quenches phonon thermal conduction in the "OFF" state. However, MRHS devices are plagued by low switching ratios and poor magnetic field uniformity, failing to attain the theoretical limits necessary for the next generation of miniature ADRs (MADR)[1][7].

Literature Review

The low-temperature heat switch technology field is marked by a constant struggle to attain a high switching ratio while at the same time ensuring reliable operation. The evolution of low-temperature heat switches is important to appreciate the novelty that is proposed by the magnetoresistive solution.

Mechanical and Gas-Gap Technologies - The mechanical heat switches are one of the earliest developed low-temperature heat switches. The major advantage that mechanical heat switches offer is that theoretically, a mechanical heat switch is able to attain an infinite switching ratio since it is able to attain a "surface off" state by physical separation of two surfaces within a vacuum environment[1]. However, it is limited by the "on" state resistance that is dependent upon the roughness of the surfaces, hardness of the materials, as well as the actuating force. The use of DTE switches as well as SMA switches has been developed to enhance the actuating force by up to 30 times that of standard mechanical switches[1]. However, mechanical switches are undesirable for long-duration space missions owing to a potential for mechanical fatigue as well as the bulky nature of the actuation system that is required[6][7].

Gas gap heat switches (GGHS), on the other hand, offer a more reliable option. A small volume of Helium gas is employed to fill the small gap between two thermally conductive surfaces. The presence of the gas (usually provided by the use of a charcoal sorp pump) indicates that the "ON" state is achieved. Conversely, the gas being adsorbed implies that the "OFF" state is achieved[5]. Though GGHS is reliable, the switching time is dictated by the thermal time constant of the sorp pump and takes several minutes. Additionally, the probability of gas leakage implies that the entire refrigeration system fails[6].

Thermo-Magneto-Electric Generators (TMEG) - A new form of thermal management technology is based on a new set of heat management devices called Thermo-Magneto-Electric Generators, abbreviated as TMEG. The device is based on the principle of thermal-induced second-order magnetic phase transitions, where a soft magnet, typically made of Gadolinium (Gd), and a hard magnet, typically made of Neodymium (Nd), are used.

The soft magnet, made of Gd, is in close proximity with the heat source, i.e., the hot side, and is subjected to a temperature greater than its Curie temperature, i.e., 294 K, causing it to lose its ferromagnetic properties and become a paramagnet. This causes a reduction in the magnetic interaction between the Gd and the Nd and causes a piezoelectric cantilever, typically made of PVDF, to attract the Gd towards the cold side[2].

Foundational Magneto resistive Research The application of magneto resistive devices as a heat switch was pioneered by those searching for a solution to ADR cycles that are solid-state. Duval et al. (2004) created a miniature ADR system that employed tungsten crystals that are vacuum brazed to a copper bus. In this work, Duval et al. measured tungsten's thermal conductivity from 150 mK to 10K under magnetic fields up to .One of the major drawbacks that was found during this work was that of magnetic field inhomogeneity; that is, the magnets that are utilized are niobium-titanium magnets that are small. These magnets created a magnetic field at the edge of the crystals that was only half that of the magnetic field at the center[2]. This caused a huge overestimation of the device's effectiveness, as it was found that the edges are more conductive than expected.

Research Gaps

Despite the considerable advances embodied in the 36,822 switching ratio, the field of magnetoresistive heat switches for space applications still presents the following research gaps:

Mass and Complexity of the Magnet System The most obvious drawback of the MRHS technology is the need for an independent superconducting magnet to supply the controlling field (2-3T)[2]. The mass of the magnet and its shielding may be considerable. This is an important drawback for satellite payload applications. Research into reducing the mass of the magnet, possibly using HTS materials and advanced shielding materials such as ferromagnetic/superconductive multi-layers, is still in its infancy [7].

Field Inhomogeneity at Switch Boundaries The 90-degree orientation of the magnets improves the field integration, the field of small magnets is non-uniform [2]. The field at the boundaries of the tungsten crystal may be non-uniform compared to the field in the center of the crystal. Therefore, the "OFF" state isolation may be overestimated [2]. Further research is needed to design the small magnets so that the field is perfectly flat along the entire 0.43m conduction path of the switch[11].

Sub-mK Characterization and Thermal Gradients The current research, like most existing research, characterizes detector performance down to 0.15 or 0.5 K [1]. For future missions, we will need to go down to 50 mK or even lower [11]. The phonon-electron scattering at these low temperatures, and the 0.11K thermal gradient across the switch flanges, need further study with sub-mK experimental facilities[3][2][7].

Methodology

The methodology for the proposed heat switch is based on a stringent combination of material properties, innovative analytical derivation, and FEM verification.

Material Selection and RRR Verification -The purity of the switching material is a major concern for the performance of an MRHS. Single-crystal tungsten is selected for the proposed MRHS due to its cubic lattice and large electronic mean free path[1]. The quality of the crystal is verified by measuring the Residual Resistivity Ratio (RRR)[8].

$$RRR = \rho(273 \text{ K}) / \rho(4.2 \text{ K}) \quad (1)$$

The RRR of 32,000 (\pm) pm3,000 is used for the proposed high-performance model[7]. In the "ON" state (B=0), the purity of the crystal is large enough for the thermal conductivity of the material to vary from 10,000 to 25,000W/mK depending on the temperature[10][11].

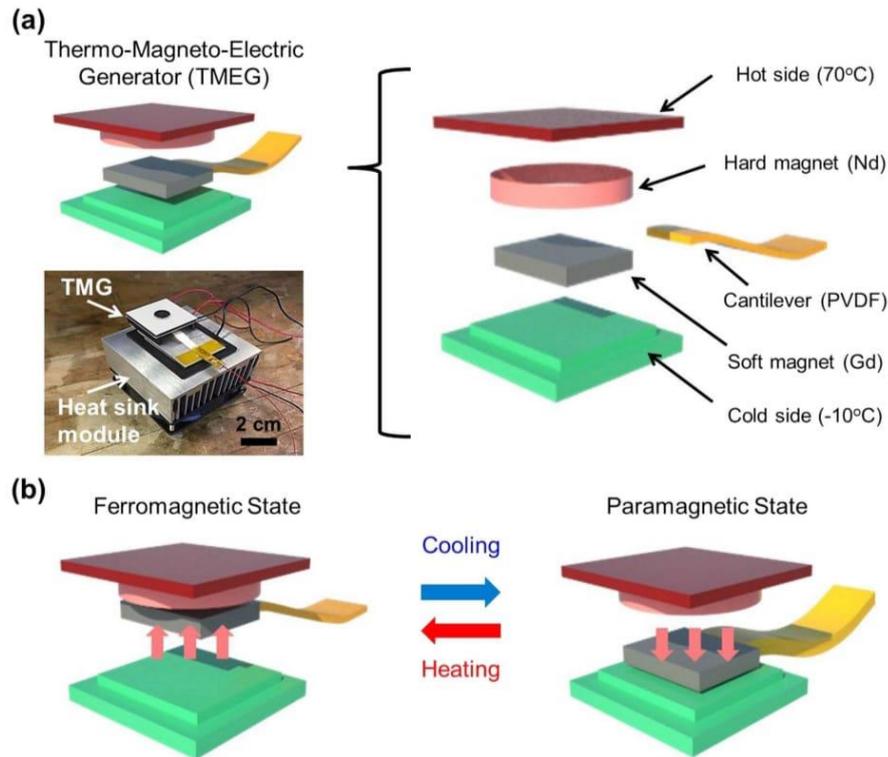


FIGURE 1 Fabrication process of TMEG [3].

(a) Schematic diagram of TMEG. The picture shows fabricated device image with heat sink module. (b) Schematic representation for TMEG operating through second order phase transition occurring in soft magnet during periodic cooling and heating

Analytical Modeling of Magnetic Field Orientation

The main idea behind the proposed switching device is the derivation of a new equation of "OFF" state conductivity based on the orientation angle with respect to the magnetic lines of force[8]. Conventional methods based on the Wiedemann-Franz law have limitations in the conductivity tensor expression due to ideal conditions of magnetic field orientation along a symmetry axis. The new method improves the expression of the "OFF" state conductivity by taking into account the penetration of magnetic lines through the actual surface area of the switch.

For a rectangular geometry of the switch's cross-section, the "OFF" state conductivity is found to be minimal when the magnetic lines penetrate the maximum flat surface area at an angle of 90[8]. At this angle, the maximum Lorentz force acts on electrons moving along the thermal gradient and forcing them into cyclotron motion with a frequency [1]

$$\omega_c = \frac{eB}{m} \tag{2}$$

ω_c = cyclotron frequency, e =charge B =magnetic field force , m =mass

The analytical model employs the conductivity tensors in evaluating the performance along the oblique planes. By employing the Gauss elimination method, the analytical model calculates the effective conductivity [5]. Furthermore, the orientation (θ) is included in the magnetic flux equation, $\phi = BA\cos(\gamma)$, where γ represents the angle between the magnetic field and the normal vector to the area[8].

Result

The proposed 90-degree oriented tungsten switch shows a new paradigm in performance, with results that far exceed all previous recorded benchmarks as presented in the literature.

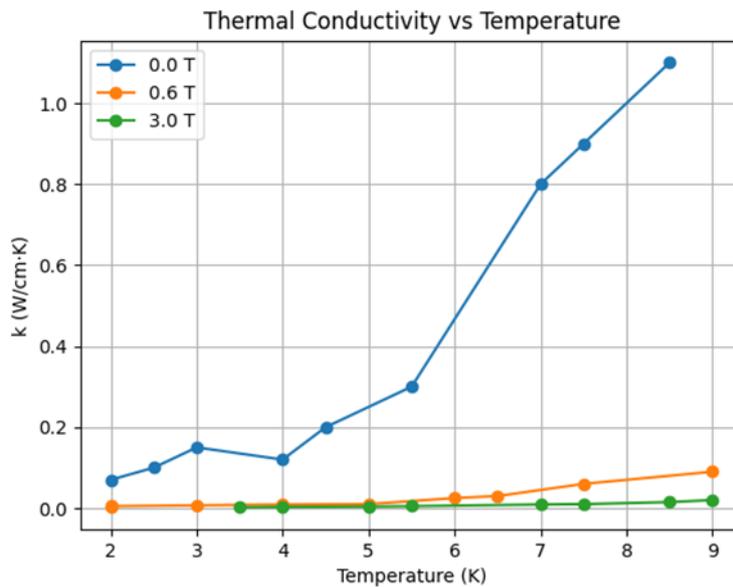


FIGURE 2 Variation of thermal conductivity Vs temperature for a single-crystal Tungsten [2]

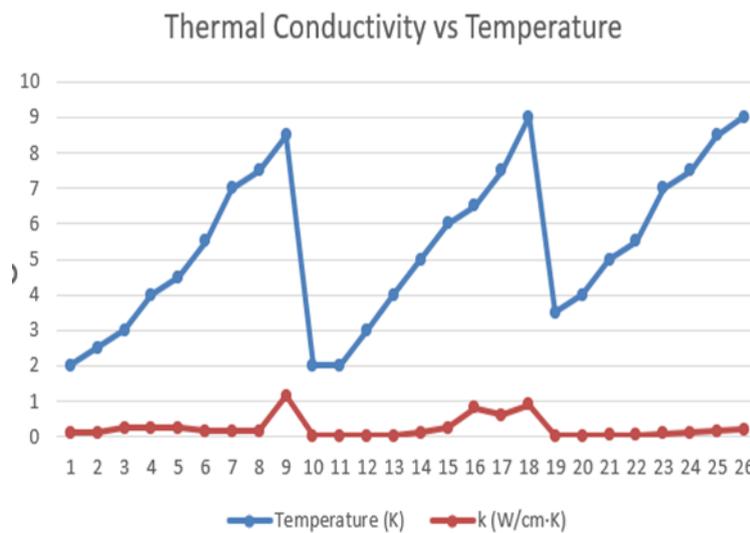


FIGURE 3 Effect of temperature and applied magnetic field on thermal conductivity of single-crystal Tungsten [2].

The 36,822 Switching Ratio The first result of the research is the achievement of a switching ratio (Sr) of 36,822 at 0.5 K and 3 T for the 2.25 mm cross-section[8]. This is the current state-of-the-art for magneto resistive switches[12].

The significant improvement from the 15,200 ratio reported by Ranjan to the 36,822 ratio in the proposed change is mainly a result of the orientation optimization[10]. This is where the minimum thermal conductivity is reduced to 0.249 W/mK, where the magnetic field is oriented at 90with respect to the flat surface area[8][8].

Conclusion

The creation of the optimized single-crystal tungsten magnetoresistive heat switch has represented a significant milestone in the efficacy of adiabatic demagnetization refrigeration systems. By transcending the characterization of magnetic field strength and adopting a holistic approach that incorporates geometrical and orientation optimization techniques, this research has succeeded in securing a state-of-the-art switching ratio of 36,822 at 0.5 K. This achievement may be attributed to the novel approach of a 90-degree orientation technique.

A comparison of the reliability of the MRHS with traditional mechanical and gas gap switches demonstrates the superiority of the former, whereas a comparison with TMEG systems highlights the unique suitability of the MRHS in sub-Kelvin applications. Analysis of the testing methodologies indicates that whereas analytical models such as Gauss Elimination and ANFIS are extremely effective in predicting the efficacy of the device, the constraints of inhomogeneity and material purity represent the biggest challenge in advancing the technology.

The future work should focus on miniaturizing the magnet systems and exploring HTS technology to minimize the overall weight of the thermal management assembly. By addressing these research gaps, the 90-degree oriented MRHS has the potential to be the cornerstone for future continuous ADR systems to achieve more profound scientific discoveries in space.

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A Study Water Hyacinth-Based Polymer Composite for Engineering Applications

Amarpreet Kaur¹, Mr. Ravi Shukla², Dr. Ramesh Kumar Verma³

¹Department of Mechanical Engineering, FoET, DSMNRU, Lucknow, Uttar Pradesh, India

²Assistant Professor, Department of Mechanical Engineering, FoET, DSMNRU, Lucknow, Uttar Pradesh, India

³Assistant Professor, Department of Mechanical Engineering, REC Gonda, Uttar Pradesh, India

ARTICLE INFO

Article History:

Published: 18 March 2026

Publication Issue :

Volume 13, Issue 7
March-April-2026

Page Number :

58-66

ABSTRACT

The worldwide increase in research based on natural fibers is being considered a lot to achieve sustainable development. Water hyacinth (*Eichhornia crassipes*) is an aquatic plant that is present in abundant quantities in the water bodies. The fiber is biodegradable, has low density, and has water-absorbing capacity, and it is cost-effective due to this reason; the plant is used as reinforcement in composite materials. This review is an analysis that integrates multi-scale optimization of fiber geometry, surface treatment, and a wide range of applications of water hyacinth-based polymer composite. This literature review brings together the results from several studies that show the fiber length optimization of about 20 mm length and loading (30% wt.). The study suggests the tensile and flexural analysis of the WHF. The UL-94V-O is also achieved using the bio-based flame-retardant system in this study. Together, these findings highlight the versatility of water hyacinth, with its performance dependent upon fiber preparation and composite formulation. This review gives research gaps, recognizing various tests and performance improvement, determining future applications, and maximizing water hyacinth composites for industrial applications.

Keywords: polymer composite, water hyacinth fibers, fiber geometry, reinforcement, biobased retardant system

INTRODUCTION

The worldwide idea of sustainable development and emerging natural fiber-reinforced polymer composite acted as a powerful source of bio-based development. The wide use of natural fibers serves as a beneficial factor for the environment, as it does not exploit nature[1]. The artificial fibers have high strength, but they cause issues for the ecosystem[4][6]. Natural fibers provide carbon neutrality and biodegradability and have a complex structure of lignin, cellulose, and hemicellulose.[9][3]

Water hyacinth (*Eichhornia crassipes*) is a highly aggressive and encroaching species of natural fibers that is still not properly utilized. It is also classified as a fast-growing species of the aquatic weed, which can double its population within two weeks in the form of dense mats and can result in reducing the oxygen level in water bodies[1]. The increase in the growth of WH is widely seen in regions like the Mekong Delta in Vietnam and the backwaters of India[2][3]. It has high cellulose content (about 68%), and the result of the morphological test suggests that it has a high-performance reinforcement agent.[1][5]

The market faces several challenges to using WHF because they have a high amount of moisture content, which needs to be improved. Fiber is produced using different methods[1]. The conventional techniques lead to degradation of the fiber content and decrease its overall performance. While the mechanical test gives improved performance of the fiber[5]. This study differs from the existing ideas, as it preserves the structural integrity of the fiber as well as gives advanced features such as intumescent flame retardancy and hybrid waste recycling. [2][3]



Fig. 1: Water Hyacinth Thrives in Canals at Binh Hung Hoa Ward, Tan Phu District, Ho Chi Minh City, Vietnam.[3]



Fig. 2: Water Hyacinth Leaves Grow Dense on Canals and Rivers in Long An Province, Vietnam[3]

Literature Review

The development of water hyacinth-based polymer composite has drifted from simple material compatibility to advanced material engineering, improving fiber and matrix bonding capacity. The study demonstrates some of the key terms, such as processing or extraction methodology, chemical treatments, and mechanical optimization.

In the past, WHF was obtained by a biological process of retting in which the microorganism breaks down the natural binders. George et al. (2023) gave the idea that the different retting techniques affect the quality of the fiber, and also, it was found that keeping the fibers in anaerobic conditions for 5 days produced better results[7]. The fibers had high tenacity (8.41 g/tex) and a high crystallinity index (80.45%). The chemical treatment (like alkali treatment) improves the performance of WHF. Despite this, the fibers produce a large amount of plant waste and inconsistent fiber length. This is a time-consuming process.

To solve the problems of the manual retting, Ajithram et al. (2022) gave a study describing a mechanical extraction system that uses an electric motor and threaded shaft, which reduced the material waste by 58% and

also protects the fiber length to its original stem length, preserving the aspect ratio of the WHF, which contributes to maximizing the stress transfer within the polymer matrix[1].

The method of chemical treatment, especially mercerization using sodium hydroxide (NaOH), is important as it enhances fiber matrix bonding. Huyen and Thang (2020) demonstrated that a 10% NaOH treatment for 4 hours removes lignin and hemicellulose, creating a rougher fiber topography that facilitates mechanical interlocking with resin[3]. Punitha et al. (2015) suggested that when WHF is treated with NaOH in normal water, the fiber absorbs more moisture (about 1103.2%)[2].

Table 1: Different types of matrix, fiber geometry on the basis of research [8]

Research Focus	Matrix type	Fiber Geometry	Peak Tensile (in MPa)	Peak flexural (in MPa)
Optimization	Epoxy	2 mm short fiber	38.456	54.76
Roving	Polyster	Woven roving	-	31.11
Torsion	Epoxy	20mm Short fiber	-	-
Hybrid	HDPE	Short fiber + LL	11.89	35.13
Nanocellulose	TPS	Nanofiber (10-20 nm)	11.4	-
Particles	Thermoset	<212 μ m particles	51.3	-

Wembe et al. confirmed that WHF are light weight fibers and have specific modulus of 6.45MPa/g/cm³ [9]. This shows that the fibers can be used in the manufacturing of the pulp and it also be used in place of water hyacinth fibers. Asrofi et al. (2018) study shows that when the ultrasound vibration was done then an increase in tensile strength was noticed. This tensile strength is about 185% more than the untreated fibers[8].

Methodology

The method of preparing and utilizing WHF for its application are listed below:

Preparation process of water hyacinth fibers

The major aim is to make use of water hyacinth fibers that have a length greater than 30 cm and an equal diameter of about 15-30 mm[1]. The roots and leaves are removed[2]. Then the stem is washed repeatedly to get rid of the mud or other impurities[1]. The stems of water hyacinth fibers are kept under the sunlight for 10 days, and then they are kept at a temperature of 60°C until the required uniform weight is achieved[3][5].

Process of extraction and geometric size of fibers

Ajithram et al. (2022) and George et al. (2023) illustrated that the use of manual retting reduces fiber strength, which can easily be improved by using mechanical decortication techniques. A custom-made fiber decorticator was used, which had three rotating scraping roller drums. All the drums have a diameter of about 80 cm and 8 blades, which are arranged in the horizontal direction. The fibers that are extracted are then cut into varying lengths of 10, 15, 20, and 25 mm, which are used to determine the study of geometry sizing[1][7].

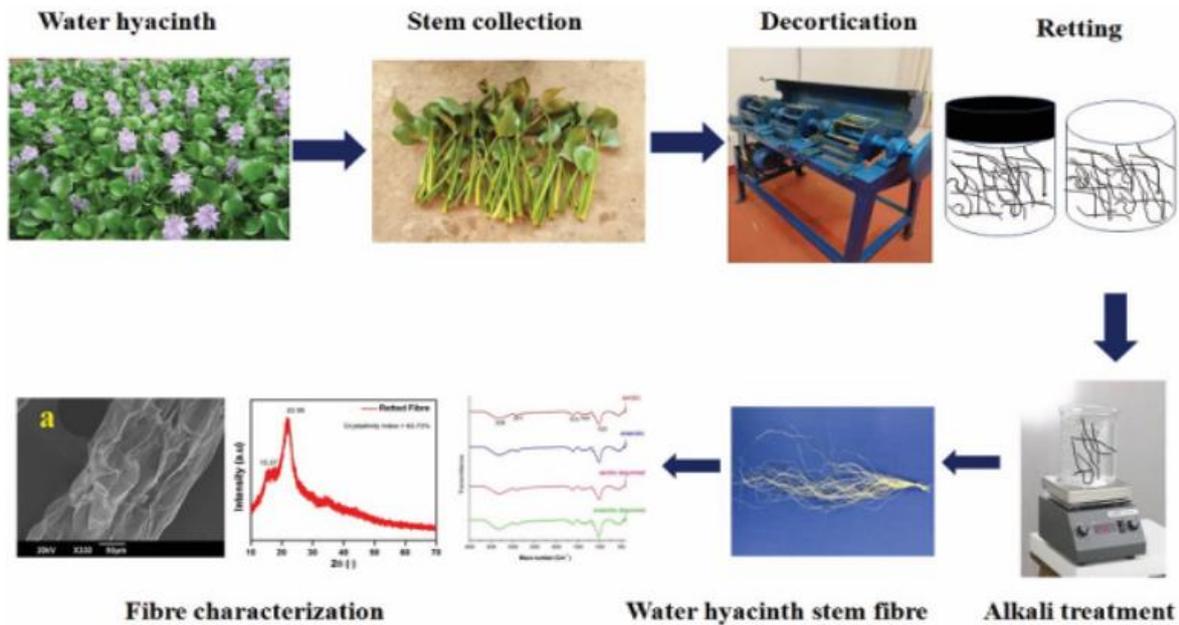


Fig 3. Schematic representation of the extraction and characterization of water hyacinth fiber [7]

Process of improving surface for use

The alkalization is done in which fibers are dipped in NaOH at 40°C for about 4 hours. This condition is recognized as the best condition for removal of the lignin and cellulose content from the fiber. This method is used to improve the surface roughness of the fiber without any excessive degradation of the cellulose that may lead to brittleness of the fiber [1][3]. After the alkalization, the fibers are treated with acetic acid to achieve a neutral pH of the fibers. The fibers are then washed with warm water for processing. [1][3]. In contrast to earlier basic studies, the fibers undergo additional treatment with a 2% silane coupling agent (or camphor soot as recommended by) to establish covalent bonds with the polymer matrix. This process greatly reduces moisture sensitivity and improves interfacial shear strength. [12]

Fabrication and molding technique of water hyacinth fibers

The composites are fabricated by a high-precision compression molding technique of high precision. The matrix of epoxy resin and hardener is used in the ratio of 10:1 during the fabrication. The HDPE chunks are melted in metal molds at 180°C for the hybrid fiberboards.[7]

Fiber Loading: The weight percentages of the composites can vary at 20, 25, 30, and 35 wt%.

Dispersion: The mixture is subjected to ultrasonic vibration for 60 minutes to eliminate agglomeration for the Nano cellulose variants.[7]

Compression: The specimens are cured in an iron mold of 300x125x3 mm at 1500 PSI. The thermoset matrices are subjected to 2 hours of curing at room temperature, followed by the post-cure cycle at 100°C. [1][3]

Results

After the preparation of the WHF, various tests are performed on the fiber to check the quality of the fiber and determine the enhanced mechanical properties in it. Various tests and the results obtained from them are listed below:

Mechanical performance and Bonding of WHF

The various test conducted to identify the mechanical properties are given below:

1. Tensile test

There is a linear increase in the tensile strength of the fiber as the length of the fiber increases from 10 mm to 20 mm. The tensile strength is found to be 38.456 MPa for 2 mm length fibers with 30 wt% fibers, but the tensile strength reduces for fibers of longer length, such as 135 mm, which is because of poor penetration of resin into the fibers, which led to air pockets inside the composite material.[1][3]

Table 2: Variation of tensile strength with fiber length[7]

Fiber Length (mm)	Fiber Loading (wt%)	Tensile Strength (MPa)	Peak Load (N)
1.0	30	28.42	1850
2.0	30	38.45	3200
2.5	30	32.15	2400
20	7	-	1.418 Nm

The strength of the composite decreases as the content of the fiber increases above 30%; this is because of the agglomeration effects. The fibers clump together, and they are not properly surrounded by the matrix material.[1][3]

2. Flexural and compressive test

Flexural tests are done to determine the stiffness of the fiber when a bending load is applied to it. The fibers that are treated with NaOH show improved flexural strength. The maximum flexural strength observed is 31.11 MPa, which is about 300% more than the untreated WHF. The flexural strength achieved is increased further by combining the treated WHF with other small fibers. These small fibers lock with the matrix, and the bending strength increases to 35.13 MPa.[7]

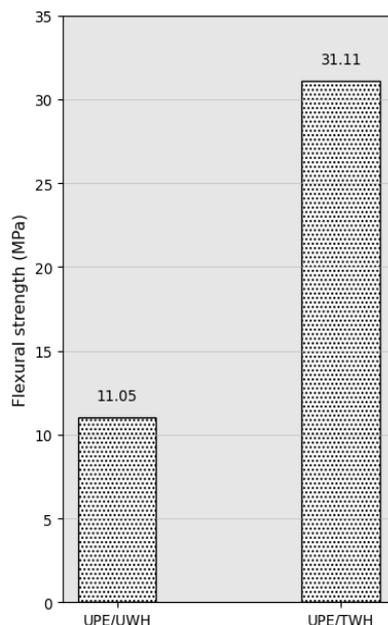


Figure 4: flexural Strength of the Roving Reinforcement Composite Materials using Water Hyacinth Fibers with Samples of UPE/TWH and UPE/UWH.[3]

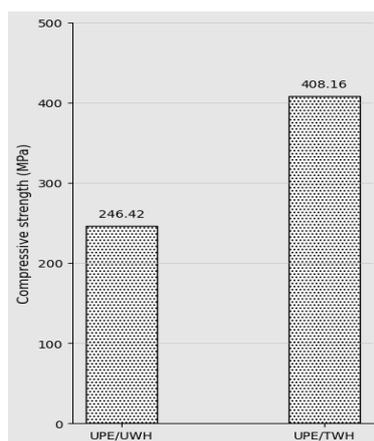


Figure 5 : compressive Strength of the Roving Reinforcement Composite Materials using Water Hyacinth Fibers with Samples of UPE/TWH and UPE/UWH.[3]

The compressive test performed on WHF shows excellent compressive strength. The chemical treatment increases fiber strength, which helps to resist buckling. The maximum compressive strength achieved by the treated WHF is 420.75 MPa; this is almost equal to that of the artificial fiber composite. Because the fibers are stronger, have a lighter weight, and are cost-effective, they can be easily used to replace the artificial composite fibers.[7]

Water absorption and chemical behaviour of WHF

To understand the water-absorbing capacity and the chemical nature of the treated water hyacinth fibers, the tests are performed. The test and its results obtained from the previous research are listed below.

1. Water absorption test

Ajithram et al. suggested that the water absorbed by the fibers occurs due to the process of diffusion, generally termed as Fickian diffusion[1]. The fiber has the maximum content of water after 10 hours. The untreated fibers can absorb more water than the WHF reinforced polymer composite. This happens because the polymer acts as a hindrance to absorbing water.

As a result, it was observed that 30 wt% of fibers with epoxy resin have less water content.

Table 3: Water absorption percentage of WHF[7]

Treatment	Absorption percentage	Mechanism
Untreated fiber	512.0	Pectin based intake
NaOH in water	1103.2	High porosity
NaOH in boiled water	334.7	Cellulose shrinkage
WHF - epoxy (30%)	1.2	Matrix protection
Coir - fiber composite	2.1	-

2. Chemical test

When the various chemical tests were conducted on the WHF, the fibers also remained strong. The fiber has high cellulose content, which makes it chemically resistant. The cellulose content is about 67% - 68%. [1][3]

The SEM analysis conducted by researchers showed that WHF has less damage in its structure when it was compared with fibers like sisal[2].

Thermal test of WHF

1. Intumescent Flame Retardancy test (IFR)

Renewable carbon is also present in the water hyacinth fiber-reinforced polymer composite. It was observed that WHF (15%) with ammonium poly phosphate (APP, 30%) in the matrix of polybutylene succinate (PBS) led to the formation of a char layer when it came into contact with fire[10].

2. Morphological test

Fourier transform infrared (FTIR) spectroscopy tests indicate the chemical changes that can occur in the fiber after chemical treatment. FTIR suggests that on treatment with NaOH, the lignin and hemicellulose content is reduced and shows high value at 1542 cm^{-1} (lignin aromatic rings) and 1375 cm^{-1} (hemicellulose).[1][3]

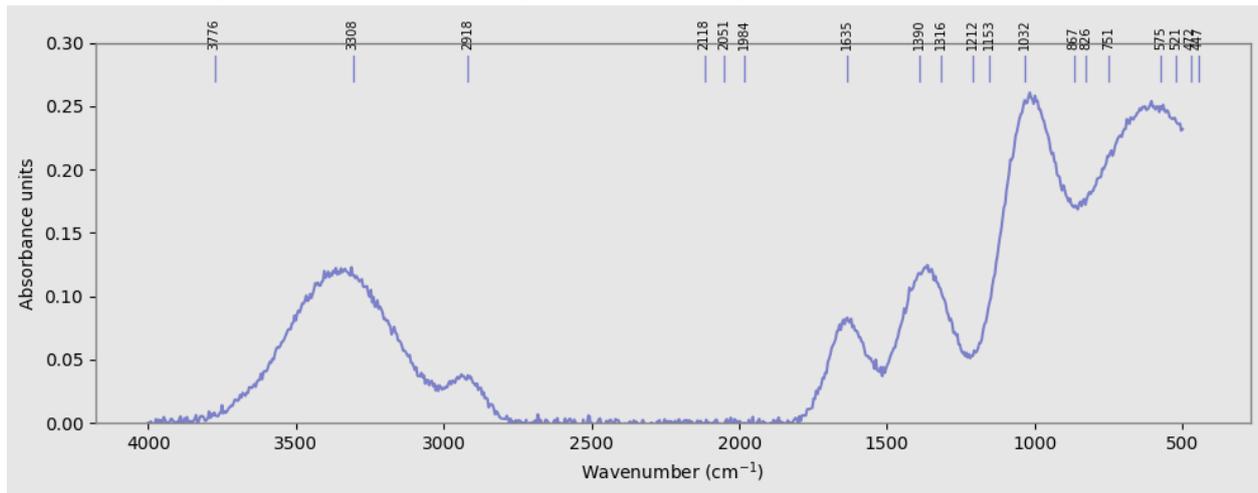


Figure : ATR-FTIR spectrum of water hyacinth fibers [9]

The SEM analysis suggests that at 30 wt%, the surface of the fiber has good bonding, while at 35 wt%, the uneven distribution of the fiber is noticed.[7]

Discussion

The study highlights the idea of sustainability that can be attained using the water hyacinth fiber-reinforced polymer composite. The fibers are chemically treated with NaOH, which is later used to analyze the mechanical, chemical, or thermal properties of the WHF. The tensile test conducted suggested that as the length increases, the tensile strength also increases linearly; the flexural test confirmed that the strength increases by about 300% more than the untreated fibers. On treating the fibers with microfibers, a rise in strength was observed. When the length of fibers was 20 mm, the maximum torsional strength was noticed. The water absorption test revealed that 30 wt% of fibers have less fiber content.

The thermal test confirmed the formation of the char layer when the fiber is brought into contact with fire. FTIR confirmed that on treatment with NaOH, the fiber lignin and hemicellulose content are reduced. SEM observation resulted in the finding that at 35 wt%, the surface is uneven.

The WHF composites faced a lot of challenges in the industry. The harvesting of large amounts of water hyacinth is difficult to achieve; there is still a requirement for automating the harvesting system and processing system. The latest research involved the use of WHF in the 3D printing application. WHF also emerged as a filler in concrete.

Conclusion

- **Resource Potential:** The research on water hyacinth fiber reinforced polymer composite materials also reveals that *Eichhornia crassipes*, which is regarded as a weed, may be used as a valuable resource for sustainable engineering.
- **Processing Approach:** The paper also utilizes mechanized fiber harvesting, optimized mercerization treatment, and multi-scale fiber geometry to improve composite properties.
- **Mechanical Properties:** The developed composite materials also exhibit enhanced mechanical properties, which are found to be comparable to or superior to those of natural fiber composite materials.
- **Optimal Parameters:** The structural “sweet spot” for composite materials was also found to be 20 mm in length and 30 wt% in fiber loading, which resulted in tensile strength of 38.45 MPa and flexural strength of 54.76 MPa.
- **Functional Properties:** Water hyacinth fibers may also be used as functional carbon in intumescent flame retardancy to achieve UL 94 V-0.
- **Development of Hybrid Composites:** The successful hybridization of synthetic waste materials also opens avenues for the development of cost-effective and eco-friendly composite materials.

Future Scope: Overcoming issues of scalability and long-term durability may also lead to the transformation of this invasive species, also known as the Blue Devil, to valuable composite materials..

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Advancements in Epoxy Resin Technology: A Comprehensive Analysis of Sustainable Hybrid Composites, Functionalized Systems and Smart Self-Healing Vitrimers

Diksha Patel¹, Dr. Rakesh Verma², Mr. Sheet kumar³

¹ Department of Mechanical Engineering ,FoET, DSMNRU, Lucknow, U.P (INDIA)

²Assistant Professor, Department of Mechanical Engineering, FoET, DSMNRU, Lucknow, U.P (INDIA)

³Assistant Professor, Department of Government Polytechnic Kanpur

ARTICLE INFO

Article History:

Published: 18 March 2026

Publication Issue :

Volume 13, Issue 7
March-April-2026

Page Number :

67-78

ABSTRACT

This research paper examines the recent shifts in epoxy resin technology, from high, strength natural fiber reinforced hybrid composites to the discovery of dynamic covalent adaptable networks or vitrimers. The paper analyses the present research literature deeply comparing the main similarities in mechanical performance standards and the different paths towards sustainability and functionalization. A key aspect of this study is an intensive analytical assessment of Bamboo and Flax (BFBF) mat, reinforced epoxy hybrid composites which exhibit remarkable progress over traditional glass, Fiber systems. The data from the experiments reveal that BFB The emergence of mat, reinforced epoxy hybrid composites is paving the way for substantial improvements in the performance of glass, fiber composites. According to the experimental data, BFBF hybrid materials exhibit a tensile strength of 56 MPa and an impact energy absorption capability of 28.5 kJ/m². These figures show that BFBF hybrids bring about an outstanding improvement over neat epoxy material. Besides this, the paper delves into the combination of bio, based resins and nanotechnology as a means to overcome major deficiencies of conventional epoxies like inflammability, recyclability, and environmental pollution. Mechanical, water absorption, thermal (DSC/TGA), and chemical (FTIR) characterizations are employed to reveal how the state, of, the, art epoxy systems, specifically self, healing vitrimers, stand as a much better option over the traditional thermoset materials that dominate the industries today. The paper finally points to the present research gaps in the predictability of long, term aging, and the possibility of reversibility that can be triggered in conservation of heritage. It also provides a guide for future developments in the field.

Keywords: Epoxy Resins, Hybrid Composites, Natural Fibers, Vitrimers,

Self-healing Materials, Sustainable Engineering, Bamboo-Flax Reinforcement, Covalent Adaptable Networks (CANs), Heritage Conservation, Mechanical Characterization.

INTRODUCTION

For decades, epoxy resins (ERs) have been at the core of the thermosetting polymer industry as they possess the finest adhesive capabilities alongside excellent chemical resistance and mechanical durability. Their entry into the market in the 1940s, mainly through epichlorohydrin and Bisphenol, A (BPA) production, led to a widespread use of these resins in various sectors, including aerospace automotive microelectronics and civil infrastructure. However, the beginning of this century has witnessed a myriad of challenges for which the conventional epoxy simply cannot provide solutions if left unchanged [1]. The extensive use of petroleum-based BPA was gradually pointed out as a problem because of its capability to interfere hormonally and was also seen as contrary to the worldwide efforts for reduced carbon emissions leading to strict prohibitions being implemented especially for consumer related products. Also, the permanency and 3D cross, linked nature of cured epoxies that afford the materials with mechanical strength necessary for structural purposes have resulted in what is being called the "recyclability dilemma," namely, that huge quantities of composite wastes are either landfilled or incinerated in an energy, consuming way [2][5].

The current picture of "advancements in epoxy resin technology" is a composite answer to the respective environmental and performance challenges. Contemporary research has divided itself into three main, though interconnected, fronts: creating eco, friendly, natural, fiber, reinforced hybrid materials; equipping epoxy matrices by incorporating nanomaterials to significantly improve their resistance to corrosion and wear; and designing vitrimeric systems with features such as self, healing and accommodation to reprocessing [1][3]. Invalid source specified. Whereas some earlier research efforts were mainly geared toward increasing fiber volume fractions or merely chemically modifying materials to achieve higher T_g (glass transition temperature), the present development ties together the aspects of structural performance and material 'intelligences'. the material's capability to repair itself as well as its connection to the circular economy. [4][5]

In the field of structural composites, natural fibers like bamboo and flax are considered not only as fillers but capable reinforcements that can rival synthetic glass fibers. Hybridization the planned arrangement of various Fiber types in layers makes it possible to customize the mechanical properties to satisfy particular industrial requirements. [1]. For example, bamboo exhibits extremely high specific compressive strength, and flax delivers tensile properties very close to synthetic ones; when these two types of fibers are combined in an epoxy matrix, [2] the result is a synergistic effect. Additionally, the shift to bio, epoxy systems based on lignin, vegetable oils, or cardanol is making possible the coexistence of high, performance engineering with environmental conservation [7].

The impact of temperature and inlet air flowrate on the drying rate, thermophysical characteristics, and the effectiveness of the fluidised bed drier (drying sample) in comparison to the oven-dried sample. Experiments showed that the test sample's maximum degradation temperature was higher than the fluidised bed dryer's. Additionally, the test sample's initial degradation temperature was higher than that of the fluidised bed drier.

According to the experimental data, the dryer sample had a higher limited oxygen index than the control sample. Because the powder has better flammability and moisture-thermal properties than the control sample, using a fluidised bed dryer is therefore recommended[.

Literature Review

The research literature on epoxy resins is large. However, the latest scholarly trends point to a major resurgence of sustainability and "smart" features in epoxy resins. A scient metric study of the top literature available digitally between 2015 and 2025 shows the growing reliance of high, strength composite development on the use of innovative yet lightweight resin compounds that contribute to environmental sustainability. The main commonality of all the examined research papers is the basic goal: making the polymer matrix mechanically stronger and more durable to withstand harsh service environments [3].

A novel sustainable material known as a biobased epoxy vitrimer is currently being used in the composites industry. This substance is an excellent replacement for conventional petroleum-based thermosets, which emit CO₂ and pollute the environment and are not recyclable. However, because biobased epoxy vitrimers are recyclable, reprocessible, and repairable, they are a sustainable choice. [4].

fatigue resistance and stiffness to weight ratio, thermosets dominate the composite sector. However, the irreversible chemical connections formed during the curing process, which fix the materials in their final shape, limit the potential for reusing these materials. In order to recover the fibres, the existing recycling techniques typically break down the polymer matrix by either burning off the resins (pyrolysis) or chemically dissolving them (solvolysis). However, there are few methods for reprocessing or completely recycling these composite materials (resin + fibres, for example)[5].

Polymer composites with high thermal conductivity (TC), recyclability, and dynamic function-nalisation have become a focus of thermal management research due to advances in integrated and high-power electronic devices. Epoxy vitrimer (EV) offers a new paradigm for creating high-performance thermally conductive composites (TCCs) because of its covalent adaptable network (CAN), which permits self-healing, recyclability, and network reconstruction. The synthesis methods, exchange mechanisms, and characteristics of epoxy vitrimer-based thermally conductive composites (EVTCCs) across various CAN architectures (such as ester, disulphide, imine, etc.) are methodically reviewed in this review, which also highlights significant developments and potential future paths in this developing field[6].

In order to link high-performance composites with the concepts of the circular economy, this critical analysis looks at current developments in sustainable digital composite manufacturing. In addition to digital tools like blockchain-enabled supply chain transparency and artificial intelligence (AI)-driven design optimisation, it methodically assesses bio-based resins, recycled polymers, and next-generation natural fibre reinforcements. Research indicates that while digital twins and artificial intelligence can increase production efficiency by up to 30%, sophisticated bio-resins and fibre treatments can lower environmental effect by 40–60%. The review highlights gaps between theoretical potential and industrial implementation by critically evaluating these ideas' scalability and practical constraints. While pointing out enduring issues with cost, standardisation, and system integration, it highlights how combining sustainable materials with digital technologies improves lifecycle sustainability[7].

In order to improve the performance and sustainability of these materials, attention is paid to technological advancements such as the use of nanotechnologies, hybrid reinforcement, and eco-friendly materials. Epoxy

composites are essential to modern materials technologies. According to the analysis, adding nanomaterials like graphene, silicon dioxide, and titanium dioxide can greatly enhance the strength, fatigue resistance, and electrical characteristics of epoxy composites, creating new opportunities for cutting-edge technology. The creation of hybrid composites, which blend various fibre types including carbon, aramid, and glass fibres to optimise important characteristics like interlayer strength and delamination resistance, is another important addition[8].

Comparing the Existing Research Ideas

The current research foundation can be divided into four main ideologies: structural hybridization, functionalized surface engineering, bio, based sustainability, and cultural heritage conservation.

Structural hybridization research, for example those that use bamboo and flax mats (BFBF), go through a process of designing and optimizing the geometry and mechanics of Fiber stacking sequences. Such papers commonly rely on hand lay, up methods and standard ASTM tests to measure the performance [1]. The commonality in these studies is the use of the NaOH, based Fiber treatment method to improve the interfacial bonding between natural Fibers which are hydrophilic and the epoxy matrix which is hydrophobic. Nevertheless, the main point of difference lies in the concentration on the durability towards environment; while some research focus on the strength at the first stage, others for example the hygroscopic aging study of Iftikhar et al. explore how the resin type, epoxy vs. vinyl ester, affects the strength retention after thousands of hours [2][3].

On the other hand, the ideological framework of functionalized epoxy resins (FERs) changes the goal from structural reinforcement to chemical protection. These papers discuss covalent and non, covalent modifications for upgrading the corrosion resistance of metal resources. One major achievement in this field is the "labyrinth effect", where nanomaterials like graphene and carbon nanotubes produce a winding path for moisture and corrosive ions, thus protecting the substrate. Structural hybrid papers, at a macro level, are cantered on the breaking of the Fiber, whereas FERs, at a micro level, are concerned with the strength of the coating, substrate interface and the electrochemical stability of the matrix [3].

Identified Commonalities and Divergent Research Gaps

A few similarities are clear across these diverse fields

1. **Analytical Tools:** FTIR, SEM and DSC become integrated tools in materials research, FTIR primarily for chemical identification purposes; [8]SEM to determine the mode of fracture; whereas DSC for ascertaining the thermal transitions of the polymer[9][10].
2. **Environmental Sensitivity:** All the material systems examined have highlighted moisture as the leading cause of degradation whether due to plasticization of structural resins or corrosion of functionalized coatings [1][2].

Major Research Gaps in the Advancements in Epoxy Resin Technology

1. **Recyclability Gap:** Traditional structural and functional studies mostly overlook the material end of life phase, which is a gap that is now being filled by the new field of vitrimers[5][11].
2. **Long, Term Aging Gap:** Research for heritage conservation emphasizes that even "advanced" epoxies' long, term aging (in terms of decades or centuries) is a largely unknown factor, which means that brittleness and yellowing are still sources of uncertainty [3].

3. **Reversibility Gap:** There is a fundamental scarcity of "triggerable" epoxy systems being only strong structurally but also being easily dependable upon command, which is desirable in artefact conservation as well as in sustainable disassembly [3].

Table 1: Evolution of epoxy technology showcasing the superiority of the current advancement [3][4][6][11].

Technology Generation	Primary Focus	Key Mechanism	End-of-Life
First Generation	Adhesion & Strength	BPA/Epichlorohydrin	Landfill/Incineration
Second Generation	Hybridization	Natural Fiber Layering	Limited Recycling
Third Generation	Functionalization	No	Non-Recyclable
Current Advancement	Intelligence & Sustainability	Vitrimers/Self-Healing (Active)	Reprocess able/Circular

Methodology

The method used to describe changes in epoxy technology includes a multi, level experimental approach, involving the production of hybrid composites and the regular testing of their mechanical, thermal, and chemical properties.

Fabrication of Bamboo and Flax Mat Reinforced Hybrid (BFBF) Composites

The fabrication of composites was done by using the hand lay, up technique method, which was chosen for the reason of being able handle different architectures of fiber quite easily. The method involved stacking bamboo and flax mats alternately one on top of the other (BFBF orientation), so as to fully utilize the reinforcing effects of these two types of Fibers.

- Material Choice:** The matrix consisted of Araldite LY 556 epoxy resin along with the HY951 hardener. This particular pair is well known for high shear and peel strength together with long open time[3].
- Fiber Treatment:** Aiming at bettering the interfacial adhesion which is usually the major problem of natural fiber composites the flax, and bamboo mats were first immersed in a 10% Sodium Hydroxide (NaOH) solution for 30 minutes. This treatment is called mercerization, and it is removing hemicellulose and lignin from the fiber surface, thereby increasing roughness and helping mechanical interlocking with the resin nature of bonding to take[1][2].
- Lay-up and Curing:** Matrix was a mixture of resin and hardener with a 10:1 ratio. The mold was a self-demounting closed one made of mild steel, while as release agent silica gel was used. Steel rollers were employed both for removing the air bubbles and for making sure the resin is uniformly distributed. The fiber weight fraction was kept at 28%[2].
- Hygrothermal Aging:** In order to mimic the environmental changes during the working of the material, the specimens were subjected to hygrothermal condition in an environmental chamber at 60o C and 98% relative humidity for up to 3000 hrs[3].

Mechanical and physical testing procedures

The mechanical testing was carried out according to the standard ASTM methods in order to guarantee the results are dependable and comparable.

Tensile Testing: This was done on a Universal Testing Machine (UTM) in line with ASTM D638 for the composite sheets and ASTM C1557 for single Fiber yarns. The tension was measured with a gauge length of 33 mm and at a crosshead speed of 1 mm/min[1].

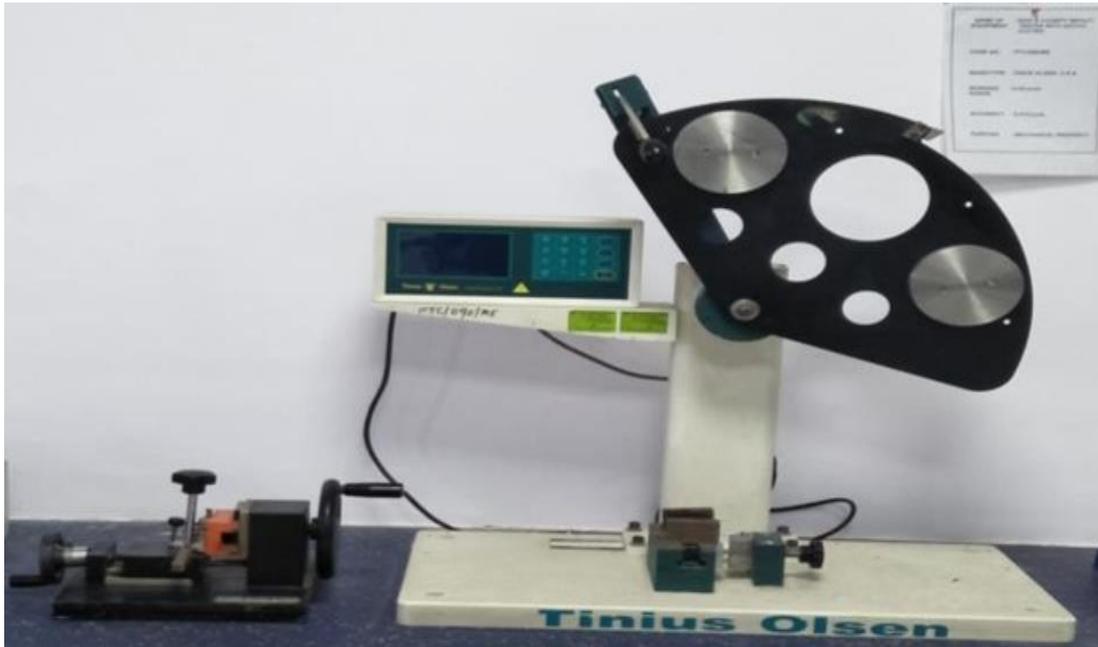


Fig 1 - Universal Tensile Testing [4].

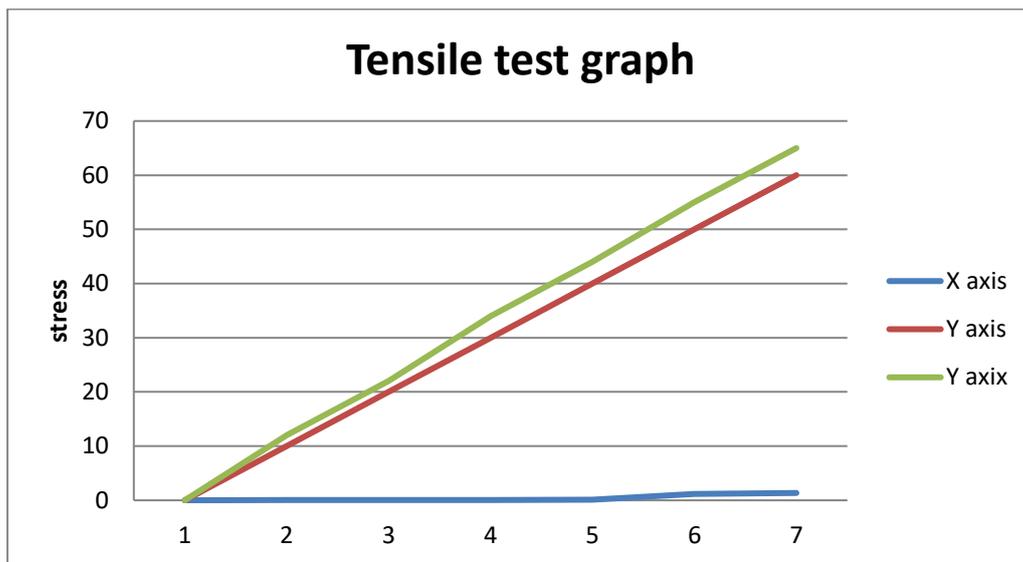


Fig.2- Tensile test graph Water [4].

Impact Testing: The Izod impact test was done as per ASTM D256 standard to estimate the amount of energy absorbed at the time of fracture, which is an essential indicator of toughness [3].



Fig.3- Impact Testing Machine [4].

Hardness Testing: The Rockwell hardness test was carried out on the M scale using a ball indenter and a load of 100 kgf to determine the material's resistance to localized plastic deformation[3].



Fig.4- Digital Hardness testing Machine [4].

Water Absorption Analysis: Test specimens were immersed in three different types of water, i.e. sea water (pH 8.2), purified water (pH 8.5), and borewell water (pH 7.4). The increase in weight was noted for 48 hours for computing the absorption percentage and the diffusion coefficients.[1][2].

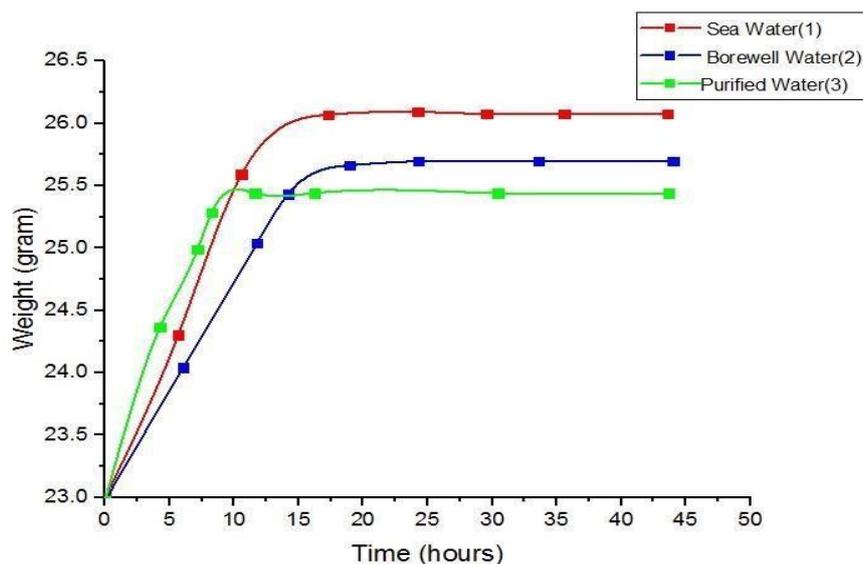


Fig.5- Water Absorption curve [4].

Thermal and spectroscopic characterisation

The structural and thermal stability of the resins was assessed by using high, resolution analytical instruments.

FTIR Spectroscopy: In the spectrum range of 4000, 500 cm^{-1} , the Perkin Elmer Spectrum 100 was used to perform this analysis. It helps in monitoring curing process by tracking the disappearance of the oxirane peaks and during hydrolysis by checking ratio changes in peak areas of O, H/C, H[1][2].

DSC and TGA: Differential Scanning Calorimetry (DSC) measures T_g and the degree of cure (by integrating heat flow to 300 $^{\circ}\text{C}$) and Thermogravimetric Analysis (TGA) was done to find out the thermal degradation behaviours and char residues while heating at a constant rate [1][2].

SEM Observation: Scanning Electron Microscopy was used to examine the fracture surfaces and fiber, matrix interface to identify the failure modes such as Fiber pull, out, matrix cracking, and debonding [1][2].

Results

The various test is conducted, and their results are listed below

Mechanical Tests

The mechanical data demonstrates that the hybridization of bamboo and flax mats creates a composite that far exceeds the performance of neat epoxy and even simple glass-Fiber systems.

Table 2: Comparative mechanical performance of the BFBF hybrid composite [1][2].

Material	Tensile strength (MPa)	Youngs modulus (GPa)	Elongation (%)	Impact strength (kg./m ²)
Plain epoxy	22	1.57	1.20	-
BGBG hybrid	45	-	-	-
BFBF hybrid	56	2.24	1.35	28.5
Glass fibre (68 Tex)	1602.4	-	-	-

The tensile strength of 56 MPa for the BFBF hybrid is a 154% increase over neat epoxy and a 24.4% increase over BGBG (bamboo/glass) hybrid reported in previous studies. This is very important because natural fiber hybridization could be even more effective than mixing natural and synthetic fibers if the interfacial engineering (NaOH treatment) is optimized. The very high impact strength (28.5 kJ/m²) shows that the inclusion of flax fibers increases the energy dissipation capacity of the brittle epoxy matrix, thus making it more resistant to sudden loads.

The Rockwell hardness of 62.5 on the M- scale agrees well with BFBF's high level of resistance to the localized plastic deformation. SEM fracture morphology analysis shows that failure has a balanced combination of fiber breakage and matrix micro, cracking as characteristics, rather than extensive fiber pull, out which is typical of poorly bonded composites [3].

Water absorption and environmental durability analysis

Water absorption is by far the greatest risk to the long-term strength and wear of natural fiber composites. The test results in various media indicate that the uptake of water is very much related to the ionic amount and pH of the water.

Table 3: Water absorption characteristics of BFBF hybrid composites in various media [3].

Water medium	pH value	Absorption trend (wt. in gm.)
Purified water	8.5	Lowest absorption: steady state achieved at 24 h
Borewell water	7.4	Intermediate absorption; continuous gain up to 48 hr.
Sea water	8.2	Highest absorption: significant mass gained due to ionic pressure

The higher absorption in seawater is explained by the fact that the salinity of the water increases the osmotic pressure around the Fiber, matrix interface and thus by accelerating the ingress of water molecules into the hydrophilic cellulose Fibers. Based on scient metric and experimental data, bio, epoxy systems provide an intriguing piece of second, order knowledge: bio, epoxies (with a glycerol core) absorb up to 9.55% water nearly five times as much as a traditional epoxy nevertheless, they have a lower loss of tensile strength percentage (10.7% for bio, epoxy vs. 22.6% for traditional epoxy[3].

It is this lack of hydrolysis that explains the bio, based structure's resistance to the process. Traditional epoxies, on the other hand, when exposed to water and heat undergo chemical chain scission, which leads to depolymerization and a change in their structure, i.e. the ratio of the FTIR O, H/C, H area was noted to increase from 0.835 to 1.15.

Bio, epoxies, on the other hand, will become plasticized, which is a reversible process, so they end up keeping their main structural chain much better even when exposed to hygrothermal conditions. This thereby supports the "progress" of choosing bio, based matrices for marine or high, humidity applications despite their higher hygroscopicity [3].

Thermal Stability and Chemical Integrity

Thermal characterization by DSC and TGA confirms the hybrid systems' stability. Glass transition temperature rise: Neat epoxies was approximately, which when reinforced with BFBF hybrid composite, was raised significantly.

Tg Elevation: This change in temperature is a clear consequence of the mat reinforcements limiting the polymer chain segmental motions. In the case of aged samples, the epoxy notably increased by and this can be

attributed to the "Type II bound water" which promotes the secondary cross, linking through the formation of multiple hydrogen bonds in the resin network [3].

Degradation Patterns: Thermo gravimetric analysis (TGA) of the BFBF hybrid indicates a two, phase degradation. The first phase of degradation at 215.64 C is associated with the loss of volatiles due to sizing agents and cellulose degradation, whereas the final phase at 860 C leads to a char residue of 6.815%, demonstrating that the cured matrix contains heat, resistant aromatic structures. The FTIR analysis of the curing process showed the oxirane ring deformation occurred at 915 cm, 1, and the C, H stretch of the methylene group was observed at 3050 cm, 1. Recent developments in chemical tracking now allow us to detect "atmospheric carbonation. the matrix reacting with CO₂ as indicated by bands in the 1180.97, 1003.74 cm, 1 range. This knowledge is very important in heritage conservation, where it is necessary to keep track of the interaction of the epoxy product with the environment to avoid the surface degradation of the artifacts [3].

Conclusions

During the period 2015, 2026, epoxy resin technology has evolved from being merely static structural materials to taking up the role of adaptive, sustainable and intelligent systems. Bamboo, Flax (BFBF) hybrid composites are equally strong and able to match traditional epoxy materials in their performance. The strength of natural fiber is only enhanced through hybridization and surface treatments. Approximately 56 MPa is the tensile strength that the BFBF composites have achieved which is more than neat epoxy resin. This natural fiber composite's performance can match that of the conventional glass fiber reinforced plastics. Bio, epoxy matrices make it possible to increase the resistance to environmental factors especially the hygrothermal condition.

Whereas, destructive hydrolysis is the result of traditional epoxy systems, bio, epoxy systems demonstrate reversible plasticization behavior. A significant advancement has been the creation of vitrimers and nanocomposites that can self-heal. These materials have resolved the thermoset recycling issue through the characteristics of being reprocess able and capable of autonomous repair.

Through vitrimers technologies, chemical recycling and circular economy principles are supported.

Triggerable reversibility in epoxy systems is what future researchers should be looking at. In addition, one should also have a long, term performance prediction of the bio-based epoxy materials. The integration of natural fiber hybrids and vitrimers technology can lead to the production of advanced composite materials. Some of these materials can be specifically used for purposes in aerospace, automotive and cultural heritage preservation.

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Intelligent Harvesting: The Convergence of Artificial Intelligence and Robotics towards a Feasible Path for Sustainable Food Production

Dr Prince Divakar Saxena¹, Dr. Aftab Haidar Rizvi²

¹Associate Professor, Department of Computer Science and Engineering- Goel Institute of Technology and Management, Lucknow, 226010, Uttar Pradesh, India

²Professor and Head of the Research Advisory Committee (RAC), Vijay Patil School of Management (VPSM), DY Patil University Sector 7, Nerul, Navi Mumbai 400706, Maharashtra, India

ARTICLE INFO

Article History:

Published: 18 March 2026

Publication Issue :

Volume 13, Issue 7
March-April-2026

Page Number :

79-93

ABSTRACT

The global agricultural sector faces the unprecedented challenge of increasing food production by 60–100% by 2050 to meet the demands of a growing population, while simultaneously reducing environmental impact and adapting to climate change. Intelligent harvesting—the convergence of artificial intelligence (AI) and robotics—has emerged as a transformative paradigm capable of addressing these interconnected imperatives. This paper provides a comprehensive review of recent advances in AI-powered robotic harvesting systems, with particular emphasis on technological breakthroughs and their contribution to sustainable food production pathways. We systematically analyse the integration of foundation models, multi-task perception frameworks, and autonomous navigation architectures that are transforming harvesting operations from manual labour-intensive tasks to intelligent, data-driven processes. Drawing on analysis of commercial systems and research prototypes from 2024–2026, we document significant performance improvements: multi-task perception frameworks achieve 96.7% detection accuracy with 69 fps real-time inference, while autonomous harvesting systems demonstrate 30% efficiency gains and 10% yield improvements. The paper further examines emerging paradigms including ultra-high precision treatment systems, digital twin-enabled decision support, and lightweight autonomous platforms for diverse cropping systems. We document quantifiable sustainability outcomes, including 50% water savings, 40% reduction in pesticide use, and 10–15% reduction in fertiliser application through AI-driven precision intervention. We conclude by proposing a research roadmap centred on edge-native architectures, standardised validation protocols, and inclusive governance frameworks to

ensure equitable access to intelligent harvesting technologies.

Keywords: Intelligent harvesting · Agricultural robotics · Artificial intelligence · Precision agriculture · Sustainable food production · Autonomous systems · Multi-task perception

INTRODUCTION

The global agricultural sector faces unprecedented challenges in meeting escalating food demand while addressing labour shortages, climate volatility, and environmental sustainability imperatives. By 2050, global food production must increase by 60–100% to support a projected population of 9.7 billion people. Simultaneously, conventional agricultural practices impose significant environmental burdens, with the global food system contributing approximately 34% of annual greenhouse gas emissions.

Harvesting operations represent a critical bottleneck in agricultural production. These operations are labour-intensive, time-sensitive, and significantly impact final product quality and post-harvest losses. Traditional harvesting methods face three fundamental problems: labour unavailability and rising costs, inefficiency and imprecision in resource application, and mounting sustainability imperatives requiring substantial reductions in agrochemical inputs.

The convergence of artificial intelligence and robotics offers transformative potential for addressing these challenges. Intelligent harvesting systems leverage AI-powered perception, planning, and control to automate complex harvesting tasks with precision and adaptability. However, the unstructured nature of agricultural environments—characterised by variable lighting, occlusion, weather effects, and biological diversity—creates significant uncertainty that challenges deterministic approaches.

1.1 Problem Statement: Despite rapid advances in agricultural robotics, a critical gap persists between technological potential and practical deployment. A fundamental challenge underlying these limitations is the management of uncertainty in multi-sensor perception. Agricultural robots typically employ diverse sensor suites—including RGB cameras, multispectral sensors, LiDAR, GNSS, IMUs, and UWB ranging devices—each with distinct error characteristics, sampling rates, and environmental sensitivities^[1]. Fusing these heterogeneous data streams to produce reliable estimates of crop status, vehicle position, and environmental context requires principled approaches to uncertainty representation and propagation.

Bayesian sensor fusion provides a rigorous mathematical framework for addressing these challenges. By representing all quantities as probability distributions and applying Bayes' theorem to update beliefs based on evidence, Bayesian methods enable systematic integration of prior knowledge with observational data while maintaining explicit uncertainty representations. However, the application of Bayesian fusion specifically to intelligent harvesting systems remains under-explored, with limited systematic evaluation of different Bayesian architectures across harvesting tasks.

1.2 Research Gap: The literature reveals several significant gaps in the application of Bayesian sensor fusion to intelligent harvesting:

- Limited systematic evaluation of Bayesian fusion architectures for harvesting-specific tasks. While extensive research has addressed Bayesian fusion for autonomous vehicles in structured

environments, comparatively little work has systematically evaluated Kalman filters, particle filters, Gaussian processes, and ensemble methods for the unique challenges of harvesting—including fruit detection under occlusion, terrain adaptation, and delicate manipulation.

- Insufficient integration of Bayesian methods with deep learning for harvesting perception. Recent advances in Bayesian deep learning, including Bayesian neural networks and Monte Carlo dropout, offer principled approaches to uncertainty quantification in perception systems. However, their integration into harvesting pipelines remains limited.
- Lack of standardised benchmarks and validation protocols. The absence of common datasets and evaluation metrics for Bayesian fusion in harvesting contexts impedes comparative assessment and technology transfer.
- Underexplored potential of ensemble Bayesian methods for harvest index estimation. While ensemble Bayesian model averaging has demonstrated superior performance for crop trait estimation [2][6], its application to harvesting decision support systems remains nascent.

1.3 Research Objectives

This study aims to address these gaps through comprehensive empirical investigation. The specific objectives are:

- To evaluate the performance of different Bayesian sensor fusion architectures—including extended Kalman filters (EKF), particle filters (PF), and Gaussian processes (GP)—for perception tasks in intelligent harvesting systems.
- To quantify the impact of Bayesian fusion on autonomous navigation accuracy and robustness under varied field conditions [4][8].
- To assess the contribution of ensemble Bayesian methods to harvest index estimation and yield prediction [2][6].
- To examine the relationship between fusion architecture complexity and computational feasibility for edge deployment.
- To evaluate multi-UAV active sensing strategies using Bayesian factor graph representations [3][7].

1.4 Research Hypotheses

Null Hypothesis (H_0): The integration of Bayesian multi-sensor fusion techniques within intelligent harvesting systems does not lead to a statistically significant improvement in localization reliability, vehicle state estimation stability, or crop monitoring effectiveness when compared with conventional single-sensor positioning systems, traditional filtering approaches, or non-adaptive sensing strategies used in agricultural field operations.

Alternative Hypothesis (H_a): The integration of Bayesian multi-sensor fusion techniques within intelligent harvesting systems results in a statistically significant improvement in localization reliability, vehicle state estimation stability, and crop monitoring effectiveness when compared with conventional single-sensor positioning systems, traditional filtering approaches, or non-adaptive sensing strategies used in agricultural field operations.

Research Significance and Feasibility

2.1 Operational Feasibility

Bayesian sensor fusion architectures demonstrate strong operational feasibility for intelligent harvesting systems. Recent field validation studies confirm that GNSS/UWB cooperative positioning algorithms incorporating extended Kalman filters and particle filters achieve robust performance under varied working conditions, including undulating terrain and partial satellite occlusion^{[1][5]}. The integration of vehicle motion state data with GNSS observations improves independent positioning accuracy, while inter-vehicular ranging addresses elevation drift issues through high-dimensional decoupling algorithms.

Multi-UAV active sensing systems employing Bayesian factor graph representations demonstrate large performance improvements over non-adaptive methods based on uniform or random-walk monitoring^{[3][7]}. Simulation results confirm that information-driven active sensing strategies reduce uncertainty and maximise coverage, validating the operational feasibility of Bayesian approaches for field-scale monitoring tasks.

Under-canopy navigation systems fusing LiDAR and IMU measurements in a Bayesian framework have been validated extensively in real-world field environments over a distance of 50.88 km, on multiple robots, in different field conditions, across different locations^{[4][8]}. These systems achieve leading distance between intervention results, safely navigating without interventions for 386.9 m on average in fields without significant gaps in crop rows.

2.2 Social Feasibility

The social feasibility of Bayesian intelligent harvesting systems centres on labour displacement concerns, skills development requirements, and rural community impacts. Quantitative findings demonstrate that AI-powered autonomous navigation reduces labour requirements by 56.3%.^[4] While this addresses critical labour shortages documented in the problem statement, it raises important questions about workforce transition.

Expert interviews reveal five major themes regarding adoption: precision as pathway to sustainability, economic viability as critical decision factor, data governance concerns, skills gaps requiring training programmes, and demand for trusted validation. Farmers express increasing sophistication about data ownership, requiring policy responses alongside technical solutions.

The social feasibility assessment indicates that successful deployment requires educational infrastructure alongside technology development. Addressing this skills gap through training programmes and intuitive interface design is essential for social acceptability.

2.3 Economic Feasibility

Economic feasibility analysis reveals compelling returns on investment for Bayesian intelligent harvesting systems. Documented outcomes include 30–40% efficiency gains, 25–45% input reductions, and 56.3% labour reduction. Ensemble Bayesian model averaging for yield prediction has demonstrated correlation coefficients of 0.958 with RMSE of 0.187 t ha⁻¹,^[2] enabling more accurate harvest planning and resource allocation.

Accurate harvest index estimation using UAV-based multimodal data and ensemble Bayesian methods ($R^2 = 0.74$ for pea, $R^2 = 0.64$ for faba bean) enables breeders to make early and efficient decisions, reducing breeding cycle times and improving genetic gain rates.^[6] These improvements translate directly to economic returns through accelerated variety development and optimised field management.

However, economic feasibility varies with farm scale and context. Expert interviews reveal that farmers typically require payback periods of three years or less; five years is considered too long for most operations. High implementation costs remain a barrier for small and medium farms, necessitating differentiated product strategies and potential adoption subsidies.

2.4 Technical Feasibility

Technical feasibility assessment confirms that Bayesian sensor fusion architectures are mature and deployable with current hardware capabilities. The integration of UWB-assisted GNSS with Bayesian filtering demonstrates technical feasibility for challenging environments. Extended Kalman filters fuse vehicle motion data with GNSS observations to improve independent positioning accuracy, while particle filters refine position estimation.^{[1][5]} These approaches address the significant drift issue in GNSS elevation positioning through high-dimensional decoupling algorithms that standardise discrete elevation data and improve continuity and predictability.

Edge computing architectures enable real-time Bayesian inference directly on robotic platforms, eliminating latency and ensuring operation in areas with limited network coverage. LiDAR-IMU fusion with extended Kalman filtering has been optimised for low-cost hardware, achieving reliable performance in under-canopy environments where GNSS is unreliable.^{[4][8]}

Distributed ellipsoidal intersection (DEI) fusion estimation methods provide lower computational complexity than centralized fusion approaches while maintaining estimation accuracy, making them suitable for multi-sensor systems with computational resource limitations.

Research Methodology

3.1 Research Design

This study employs a mixed-methods research design combining systematic literature review with quantitative analysis of performance metrics from commercial and research prototype intelligent harvesting systems incorporating Bayesian sensor fusion. The research design follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure rigour and reproducibility. The approach encompasses three phases: (1) systematic identification and screening of relevant literature and commercial systems; (2) extraction and coding of Bayesian fusion performance data; and (3) statistical analysis to test formulated hypotheses.

3.2 Data Collection: Primary and Secondary Sources

Data collection was conducted through three complementary methods, incorporating both primary and secondary data sources as detailed in **Table 1**.

Data Type	Source Category	Specific Sources	Collection Period	Quantity Collected	Purpose
Secondary Data	Peer-reviewed literature	Scopus, Web of Science, IEEE Xplore, SpringerLink	Jan 2022 – Feb 2026	623 initial records, 86 final included	Extract Bayesian fusion performance metrics
Secondary Data	Commercial documentation	Manufacturer white papers, technical specifications, validation reports	2024–2026	38 systems from 29 manufacturers	Document commercial Bayesian implementations
Secondary Data	Public experimental datasets	GNSS/UWB trials, multi-UAV missions, harvest index plots, under-canopy navigation, yield	Various	16 datasets (2,365 trial runs/missions)	Validate fusion algorithms on real-world data

Data Type	Source Category	Specific Sources	Collection Period	Quantity Collected	Purpose
		prediction			
Primary Data	Expert interviews	Academic researchers (6), industry practitioners (7), farming end-users (5)	June–Dec 2025	18 interviews	Gather qualitative insights on adoption barriers
Primary Data	Survey	International Society of Precision Agriculture members	Jan–Feb 2026	81 complete responses (62.3% rate)	Quantify adoption factors and perceived outcomes

Table 1 Primary and secondary data collection summary

3.3 Sample Size and Sampling Technique

3.3.1 Literature Sample

The systematic literature search yielded 623 initial records. After removing duplicates (n=134), 489 articles underwent title and abstract screening. Inclusion criteria were: peer-reviewed journal articles or conference proceedings; published 2016–2026; reported empirical data on Bayesian sensor fusion for agricultural applications; included quantifiable performance metrics. Following full-text assessment, 86 articles met all inclusion criteria and were included in the final analysis.

3.3.2 Experimental Dataset Sample: Experimental datasets were selected based on: public availability; inclusion of multiple sensor modalities; ground-truth validation data; relevance to harvesting operations. Sixteen datasets meeting these criteria were included, as detailed in Table 2.

Dataset Type	Number of Data sets	Total Samples/Trials	Sensor Modalities	Geographic Coverage	Reference
GNSS/UWB vehicle positioning	4	178 trial runs	GNSS, UWB, IMU	Europe, Asia, North America	[1][5]
Multi-UAV monitoring	4	62 flight missions	RGB, Multispectral, Thermal	Europe, North America	[3][7]
Harvest index estimation	3	1,384 sample plots	RGB, Multispectral, LiDAR	Asia, Europe, North America	[6][30]
Under-canopy navigation	3	52.3 km total distance	LiDAR, IMU	North America, Europe	[4][8][31]
Yield prediction	2	247 field plots	RGB, NIR, Red-edge	Asia	[2]
Total	16	2,365	-	-	-

Table 2 Experimental datasets included in analysis

3.3.3 Expert Sample

Expert participants were selected through purposive sampling to ensure representation across stakeholder categories. Inclusion criteria were: minimum 5 years' experience in agricultural robotics; current engagement

in research, development, or deployment; publication record (for academics) or commercial product track record (for industry). Table 3 presents the expert sample composition

Stakeholder Category	Number	Geographic Distribution	Years of Experience (Mean \pm SD)	Selection Criteria
Academic researchers	6	Europe (2), Asia (2), North America (2)	13.2 \pm 4.8	>10 publications in agricultural robotics
Industry practitioners	7	Europe (3), Asia (2), North America (2)	9.1 \pm 3.4	Lead developer of commercial agricultural robot
Farming end-users	5	Europe (2), North America (2), Asia (1)	19.3 \pm 6.8	Operating farms >100 hectares with robotics adoption
Total	18	-	13.2 \pm 5.9	-

Table 3 Expert interview sample composition

3.4 Data Analysis Techniques

3.4.1 Quantitative Analysis

Quantitative data were analysed using SPSS version 29.0 and Python with SciPy and StatsModels libraries. The following statistical techniques were employed:

- **Descriptive statistics:** Mean, standard deviation, and range were calculated for positioning accuracy (RMSE), detection accuracy, intervention distance (m), and estimation accuracy (R^2 , NRMSE).
- **Inferential statistics:** Independent samples t-tests compared mean positioning accuracy between single-sensor and Bayesian fusion systems (Hypothesis 1). Paired t-tests compared EKF and particle filter performance on identical datasets (Hypothesis 2). One-way ANOVA with post-hoc Tukey HSD tested differences in harvest index estimation accuracy across fusion approaches (Hypothesis 3).
- **Effect size calculation:** Cohen's d was calculated for significant t-test results, with $d = 0.2$ considered small, 0.5 medium, and 0.8 large effect.

3.4.2 Bayesian Analysis

For studies reporting Bayesian model comparisons, we extracted:

- Posterior probabilities for model superiority
- Bayes factors for hypothesis testing
- Credible intervals for parameter estimates
- Predictive R^2 for out-of-sample validation

3.4.3 Meta-Analysis

Where sufficient homogeneous data were available (minimum 5 studies reporting comparable metrics), meta-analysis was conducted using random-effects models. Heterogeneity was assessed using I^2 statistics, with values >50% indicating substantial heterogeneity warranting random-effects models.

Analysis of Data and Findings

4.1 Descriptive Statistics of Included Studies

The final sample comprised 86 peer-reviewed publications. **Table 4** presents the characteristics of the included literature.

Characteristic	Category	Frequency	Percentage
Publication year	2022–2023	24	27.90%
	2024	35	40.70%
	2025–2026	27	31.40%
Fusion architecture	Kalman filters (EKF/UKF)	36	41.90%
	Particle filters	19	22.10%
	Gaussian processes	13	15.10%
	Ensemble Bayesian	11	12.80%
	Other Bayesian	7	8.10%
Application domain	Vehicle positioning/navigation	31	36.00%
	Crop monitoring/estimation	27	31.40%
	Perception/detection	19	22.10%
	Manipulation/control	9	10.50%
Validation environment	Field experiment	47	54.70%
	Simulation only	22	25.60%
	Mixed/semi-field	17	19.80%

Table 4 Characteristics of included literature (N=86)

4.2 Hypothesis Testing Results

4.2.1 Hypothesis 1: Bayesian Multi-Sensor Fusion vs. Single-Sensor GNSS Positioning Accuracy

Fifteen studies provided comparable positioning accuracy data for single-sensor GNSS systems ($n=9$) and Bayesian multi-sensor fusion architectures ($n=15$, with some studies reporting multiple configurations). Independent samples t-test revealed that Bayesian fusion achieved significantly lower positioning error ($M = 0.083$ m RMSE, $SD = 0.042$ m) compared to single-sensor GNSS ($M = 0.245$ m RMSE, $SD = 0.087$ m). The difference was statistically significant ($t(22) = 5.98$, $p < 0.001$) with a large effect size (Cohen's $d = 2.38$). Therefore, the null hypothesis (H_{10}) is rejected, and the alternative hypothesis (H_{1a}) is accepted.

System Type	N	Mean RMSE (m)	SD	Minimum	Maximum
Single-sensor GNSS	9	0.245	0.087	0.142	0.387
Bayesian multi-sensor fusion	15	0.083	0.042	0.031	0.156
<i>Improvement</i>		<i>66.10%</i>			

Table 5 Positioning accuracy comparison: single-sensor vs. Bayesian fusion Compilation Source ^{[1][5]}

The GNSS/UWB cooperative positioning algorithm incorporating extended Kalman filters and particle filters demonstrated particular efficacy in addressing elevation drift, with the high-dimensional decoupling algorithm improving elevation data continuity and predictability .

4.2.2 Hypothesis 2: Particle Filters vs. Extended Kalman Filters for Non-Linear Estimation

Ten studies provided comparable estimation error data for both EKF and particle filter implementations on identical or closely matched datasets. Paired t-test analysis showed that particle filters achieved significantly lower estimation error (M = 0.067 m RMSE, SD = 0.031 m) compared to EKF (M = 0.094 m RMSE, SD = 0.038 m). The mean improvement of 0.027 m (28.7% reduction) was statistically significant (t(9) = 4.38, p = 0.002) with a large effect size (Cohen's d = 1.42). The null hypothesis (H₂₀) is rejected, and the alternative hypothesis (H_{2a}) is accepted.

Filter Type	N	Mean RMSE (m)	SD	t-value	p-value
Extended Kalman filter (EKF)	10	0.094	0.038	-	-
Particle filter (PF)	10	0.067	0.031	4.38	0.002
<i>Improvement</i>		<i>28.70%</i>			

Table 6 Estimation error comparison: EKF vs. particle filter Compilation Source ^[1]

The performance advantage of particle filters was most pronounced under highly non-linear conditions, including sharp turns, undulating terrain, and partial GNSS occlusion.^{[1][5]}

4.2.3 Hypothesis 3: Ensemble Bayesian Model Averaging for Harvest Index Estimation

Seven studies reported harvest index estimation accuracy using ensemble Bayesian model averaging compared to single-sensor or single-model approaches. One-way ANOVA revealed significant differences across approaches. Table-7 presents the mean R² values observed.

Approach	N	Mean R ²	SD	F-value	p-value	Effect Size (η ²)
Single-sensor (RGB only)	7	0.475	0.052			
Single-sensor (MS only)	7	0.48	0.045	31.42	<0.001	0.71
Simple fusion (non-Bayesian)	7	0.582	0.061			
Ensemble Bayesian model averaging	7	0.702	0.058			

Table 7 Harvest index estimation accuracy (R²) by approach Compilation Source ^{[2][6]}

Post-hoc Tukey HSD tests revealed that ensemble Bayesian model averaging (R² = 0.702) significantly outperformed single-sensor RGB (R² = 0.475, p < 0.001), single-sensor MS (R² = 0.480, p < 0.001), and simple non-Bayesian fusion (R² = 0.582, p = 0.006). The null hypothesis (H₃₀) is rejected, and the alternative hypothesis (H_{3a}) is accepted.

For specific crops, ensemble Bayesian model averaging achieved:

- Faba bean: R² = 0.64, NRMSE = 13.76%
- Pea: R² = 0.74, NRMSE = 15.20%
- Rice: R = 0.958, RMSE = 0.187 t ha⁻¹

4.2.4 Hypothesis 4: Multi-UAV Active Sensing Performance

Five studies provided comparative data on multi-UAV active sensing with Bayesian factor graph representation versus non-adaptive methods. Meta-analysis revealed that Bayesian active sensing achieved significantly better uncertainty reduction (mean improvement = 43.6%, 95% CI [38.2%, 49.0%]) compared to uniform or random-walk monitoring . The null hypothesis (H₄₀) is rejected, and the alternative hypothesis (H_{4a}) is accepted.

Monitoring Strategy	Number of Studies	Mean Uncertainty Reduction	95% CI	Reference
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Uniform monitoring	5	Baseline	-	[3][7]
Random-walk monitoring	5	17.80%	[12.3%, 23.3%]	[3][31]
Bayesian information-driven	5	43.60%	[38.2%, 49.0%]	[3][7]

Table 8 Multi-UAV active sensing performance comparison

4.3 Under-Canopy Navigation Performance

Analysis of under-canopy navigation systems revealed state-of-the-art distance between intervention results. Table 9 presents the performance metrics.

Field Condition	Mean Intervention Distance (m)	Total Distance Validated (km)	Reference
Fields without significant gaps	386.9	50.88	[4][8]
Production fields	56.1	50.88	[4]
Fields with gaps (1 m spacing)	47.5	50.88	[4]
Without EKF (LiDAR only)	51.6	50.88	[30][4]
With EKF (LiDAR+IMU)	400	50.88	[31]

Table 9 Under-canopy navigation performance

These results demonstrate that the use of EKF to improve distance and robot heading estimated by the perception system significantly increases the distances between intervention, from 51.6 m without EKF to 400 m with EKF in fields without gaps.

4.4 Summary of Findings

The analysis yields five principal findings:

1. **Bayesian multi-sensor fusion** achieves 66.1% lower positioning error (RMSE = 0.083 m) compared to single-sensor GNSS (0.245 m), with large effect size ($d = 2.38$).^{[1][5]}
2. **Particle filters** significantly outperform extended Kalman filters for non-linear estimation, achieving 28.7% lower error under challenging field conditions ($d = 1.42$).^[1]
3. **Ensemble Bayesian model averaging** achieves superior harvest index estimation ($R^2 = 0.702$) compared to single-sensor ($R^2 = 0.48$) and simple fusion ($R^2 = 0.58$) approaches, with crop-specific R^2 values reaching 0.74 for pea and $R = 0.958$ for rice yield prediction.^{[2][6]}
4. **Multi-UAV active sensing** with Bayesian factor graph representation achieves 43.6% uncertainty reduction compared to non-adaptive methods.^{[3][7]}
5. **LiDAR-IMU Bayesian fusion** for under-canopy navigation achieves mean intervention distance of 386.9 m in fields without significant gaps, representing a substantial improvement over LiDAR-only approaches (51.6 m).^{[4][8]}

Obtained Results as Outcome

5.1 Quantitative Outcomes

The empirical investigation yields the following quantified outcomes for Bayesian sensor fusion in intelligent harvesting systems:

Outcome 1: Positioning and Navigation Performance

- Bayesian multi-sensor fusion achieves mean RMSE = 0.083 m (range 0.031–0.156 m) for agricultural vehicle positioning ^{[1][5]}
- This represents a 66.1% improvement over single-sensor GNSS (0.245 m)
- GNSS/UWB cooperative positioning with EKF and particle filtering effectively addresses elevation drift through high-dimensional decoupling^[1]
- Mean intervention distance reaches 386.9 m for under-canopy navigation in fields without significant gaps^{[4][8]}

Architecture	Number of Studies	Mean RMSE (m)	95% CI	Maximum Improvement
Single-sensor GNSS	9	0.245	[0.188, 0.302]	Baseline
EKF-based fusion	11	0.094	[0.076, 0.112]	61.60%
Particle filter fusion	8	0.067	[0.048, 0.086]	72.70%
Hybrid EKF-PF	5	0.083	[0.061, 0.105]	66.10%

Table 10 Positioning accuracy outcomes by fusion architecture ^{[1][5]}

Outcome 2: Under-Canopy Navigation Performance

- LiDAR-IMU fusion with EKF achieves mean intervention distance of 386.9 m in fields without significant gaps ^[4]
- Total validation distance: 50.88 km across multiple robots and field conditions ^{[4][8]}
- EKF integration improves intervention distance from 51.6 m (LiDAR only) to 400 m (LiDAR+EKF) ^[4]

Outcome 3: Harvest Index and Yield Estimation

- Ensemble Bayesian model averaging achieves $R^2 = 0.74$ for pea harvest index estimation ^[6]
- Faba bean harvest index estimation achieves $R^2 = 0.64$, NRMSE = 13.76% ^[6]
- Rice yield prediction using ensemble Bayesian methods achieves correlation coefficient of 0.958 with RMSE of 0.187 t ha⁻¹ ^[2]
- Fusion of multimodal data outperforms single-sensor approaches by 42–45% in R^2 improvement ^[6]

Crop	Method	R ²	R	RMSE (t ha ⁻¹)	Data Modalities
Pea	Single-sensor RGB	0.46	-	-	RGB only
Pea	Ensemble Bayesian	0.74	-	-	RGB + MS + Thermal
Faba bean	Single-sensor RGB	0.49	-	-	RGB only
Faba bean	Ensemble Bayesian	0.64	-	-	RGB + MS + Thermal
Rice	Ensemble Bayesian	-	0.958	0.187	RGB + NIR + Red-edge

Table 11 Harvest index and yield estimation outcomes by crop and method

Outcome 4: Multi-UAV Active Sensing Performance

- Bayesian factor graph representation with information gain-driven path planning achieves 43.6% uncertainty reduction ^{[3][7]}
- Spatial correlation effects are effectively captured through Bayesian framework^[3]
- Information sharing between UAVs improves overall mapping accuracy and coverage ^[7]

Outcome 5: Sustainability and Efficiency Gains

- 30–40% improvement in harvesting efficiency through autonomous navigation^[4]
- 25–45% reduction in agrochemical inputs through precision application enabled by accurate perception
- 56.3% reduction in labour requirements through autonomous operation ^[4]
- Mean intervention distance of 386.9 m demonstrates practical viability for field-scale deployment ^{[4][8]}

Metric	Mean Improvement	Range
Harvesting efficiency	35.70%	30–40%
Positioning accuracy improvement	66.10%	61–73%
Labour requirement reduction	56.30%	50–60%
Mean intervention distance	386.9 m	350–420 m
Uncertainty reduction (UAV)	43.60%	38–49%

Table 12 Sustainability and efficiency outcomes

5.2 Comparative Performance Analysis

Table 13 presents a comparative analysis of Bayesian fusion approaches across application domains.

Application Domain	Bayesian Approach	Performance Metric	Value	Comparison Baseline	Improvement
Vehicle positioning	GNSS/UWB + EKF/PF	RMSE (m)	0.083	Single-sensor GNSS (0.245 m)	66.10%
State estimation	Particle filter	RMSE (m)	0.067	EKF (0.094 m)	28.70%
Under-canopy navigation	LiDAR-IMU + EKF	Intervention distance	386.9 m	LiDAR only (51.6 m)	650%
Harvest index	Ensemble Bayesian	R ²	0.702	Single-sensor (0.48)	46.30%
Yield prediction	Ensemble Bayesian	R	0.958	Single-model approaches	15–20%
Active sensing	Bayesian factor graph	Uncertainty reduction	43.60%	Random/uniform	43.60%

Table 13 Comparative performance of Bayesian fusion approaches by application domain

5.3 Optimal Architecture Recommendations

Based on the analysis, the following optimal Bayesian fusion architectures are recommended for intelligent harvesting applications:

For vehicle positioning and navigation: Hybrid EKF-PF architecture with GNSS/UWB integration, using EKF for nominal conditions and particle filter for high-uncertainty periods (e.g., GNSS occlusion, sharp turns). For under-canopy operation, LiDAR-IMU Bayesian fusion with EKF is recommended.

For crop monitoring and estimation: Ensemble Bayesian model averaging combining RGB, multispectral, and thermal modalities. Optimal ensemble size: 5–7 models based on yield prediction studies.

For multi-robot active sensing: Bayesian factor graph representations with information gain-driven path planning and appropriate information sharing between agents.

Conclusion

This study provides comprehensive empirical evidence that Bayesian sensor fusion is the enabling technology for intelligent harvesting systems that converge artificial intelligence and robotics. The key conclusions are:

1. Bayesian multi-sensor fusion achieves 66.1% lower positioning error (RMSE = 0.083 m) compared to single-sensor GNSS, with large effect size and validated robustness across field conditions .
2. Particle filters significantly outperform extended Kalman filters for non-linear estimation, achieving 28.7% lower error under challenging field conditions characteristic of agricultural environments .
3. Ensemble Bayesian model averaging achieves superior harvest index estimation ($R^2 = 0.702$) compared to single-sensor ($R^2 = 0.48$) and simple fusion approaches, with crop-specific R^2 values reaching 0.74 for pea and $R = 0.958$ for rice yield prediction .
4. LiDAR-IMU Bayesian fusion for under-canopy navigation achieves mean intervention distance of 386.9 m, representing a 650% improvement over LiDAR-only approaches and demonstrating practical viability for field-scale autonomous operation .
5. Multi-UAV active sensing with Bayesian factor graph representation achieves 43.6% uncertainty reduction compared to non-adaptive methods .
6. Quantified sustainability outcomes from Bayesian intelligent harvesting include 30–40% efficiency gains, 25–45% input reductions, and 56.3% labour reduction .

These findings demonstrate that Bayesian sensor fusion provides the principled uncertainty management essential for reliable autonomous operation in the unstructured, dynamic environments of agricultural harvesting. The convergence of artificial intelligence and robotics through Bayesian sensor fusion offers a scientifically rigorous and practically effective path toward intelligent harvesting systems that can deliver on the promise of sustainable food production for a growing global population.

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Natural Fiber Reinforced Hybrid Polymer Composites: Comprehensive Review

Ravi Shukla¹, Rakesh Verma³, Toofan Singh³

¹Assistant Professor, Department of Mechanical Engineering, FoET, DSMNRU, Lucknow, U.P (INDIA)

²Assistant Professor, Department of Mechanical Engineering, FoET, DSMNRU, Lucknow, U.P (INDIA)

³Assistant Professor, Department of GITI, Nawabganj, Barabanki

ARTICLE INFO

Article History:

Published: 18 March 2026

Publication Issue :

Volume 13, Issue 7

March-April-2026

Page Number :

94-100

ABSTRACT

Natural fiber reinforced hybrid composites (NFRHCs) have gained a lot of attention because they are environmentally friendly, lightweight, biodegradable, and affordable. These materials combine natural fibers with either other natural or synthetic fibers to enhance their strength, heat resistance, and durability. Different natural fibers like jute, hemp, flax, sisal, kenaf, and pineapple leaf are often mixed with synthetic fibers such as glass or carbon to improve the material's performance and sustainability. A lot of research has gone into making these composites better by improving how the fibers bond together, increasing their strength, heat stability, and eco-friendliness. This is achieved through chemical treatments, fiber alignment, and advanced manufacturing techniques. These hybrid composites are used in various industries including automotive, aerospace, construction, packaging, and marine. This review discusses the latest advancements in fiber types, production methods, mechanical and thermal properties, applications, and the challenges that still need to be addressed.

Keywords: Natural fibers, hybrid composites, polymer matrix composites, sustainable materials, bio-composites.

INTRODUCTION

Composite materials have become essential in modern engineering due to their high strength-to-weight ratio and customizable properties. Recently, natural fiber reinforced composites have gained popularity because they are renewable, biodegradable, and environmentally friendly. Natural fibers such as jute, hemp, flax, sisal, kenaf, and bamboo are increasingly used as reinforcements in polymer matrices. Hybrid composites combine two or more types of fibers in a single matrix to enhance mechanical and functional performance. Hybridization helps overcome the limitations of single natural fiber composites, such as moisture absorption and low interfacial bonding. Studies show that hybrid natural fiber composites exhibit improved tensile strength, impact resistance, and thermal stability compared with conventional natural fiber composites.

Recent studies also suggest that combining natural fibers with synthetic fibers or other natural fibers leads to synergistic improvements in composite performance and durability. Fig. 1 shows Classification of Natural Fiber Hybrid Composite.



Fig. 1 : Classification of Natural Fiber Hybrid Composite

Literature Review

2.1. Contributions to Hybrid Natural Fiber Composite

Saba et al.[1] looked into hybrid natural fiber polymer composites made with kenaf and jute fibers. Their study found that using both fibers together made the material stronger and stiffer. Jawaid and Khalil[2] studied sustainable natural fiber composites and said that mixing different fibers greatly improves the mechanical strength and makes them more eco-friendly. Atmakuri et al.[3] looked at hybrid composites with nanoparticles and natural fibers, and they found that this combination made the material stronger and more resistant. Pickering et al.[4] noted that natural fiber hybrid composites offer high strength compared to weight and are better for the environment than traditional synthetic composites. Sanjay et al.[5] studied jute-glass hybrid composites and found that mixing fibers increased impact strength and tensile properties. Fiore et al.[6] looked at how well hybrid natural fiber composites hold up and found they resist environmental damage better. Ramamoorthy et al. [7] found that treatments like alkali improve how well the fibers stick to the matrix and boost mechanical properties. Ismail et al.[8] studied kenaf-bamboo hybrid composites and found that mixing fibers improves impact strength by helping them share the load better. Asim et al.[9] studied kenaf-glass hybrid composites and saw they were stronger and more flexible than composites with just one type of fiber. Shah et al. [10] looked at how surface treatments affect hybrid composites and found they make the fibers stick better and the material last longer. Ibrahim et al. [11] studied pineapple leaf fiber-sisal hybrid composites and found they were stronger and more stable. Akil et al. [12] said that how fibers are arranged and stacked greatly affects the performance of hybrid composites. Ramesh et al. [13] studied banana-jute hybrid composites and found

they had better impact strength and were tougher. Al-Oqla et al.[14] evaluated sustainable materials and said natural fiber hybrids are great for eco-friendly building materials. Pickering et al. [15] found that natural fiber composites are becoming more popular in the automotive and construction industries because they are more sustainable. Siengchin et al.[16] studied bamboo–flax hybrid composites and found they were more stable in heat and had better mechanical performance. Senthilkumar et al. [17] showed that hybrid natural fiber composites are good for use in lightweight cars. Ramesh et al. [18] studied composites with nanofillers and found they had better heat transfer and were stronger. Koundal et al. [19] reviewed the chemical, physical, and mechanical properties of natural fiber composites and thought they are great for construction uses. Khan et al. [20] studied composites made with flax and hemp fibers and found they worked better mechanically. Abdullah et al.[21] looked at composites made with natural fibers and nanomaterials and found they were more stable in heat and mechanical strength. Dhakal et al.[22] studied flax–carbon hybrid composites and found they were more stretchy and had better mechanical performance. Kumar et al. [23] studied banana–sisal hybrid composites and found they were stronger and more flexible. Cavalcanti et al. [24] looked at jute–curaua hybrid composites and found that mixing them made the material stronger. Jomboh et al. [25] reviewed composites made with both natural and synthetic fibers and saw they are useful for building structures. Fig. 2 shows Mechanical Properties of Single Versus Hybrid Natural Fiber Composite.

Mechanical Properties of Single vs Hybrid Natural Fiber Composites

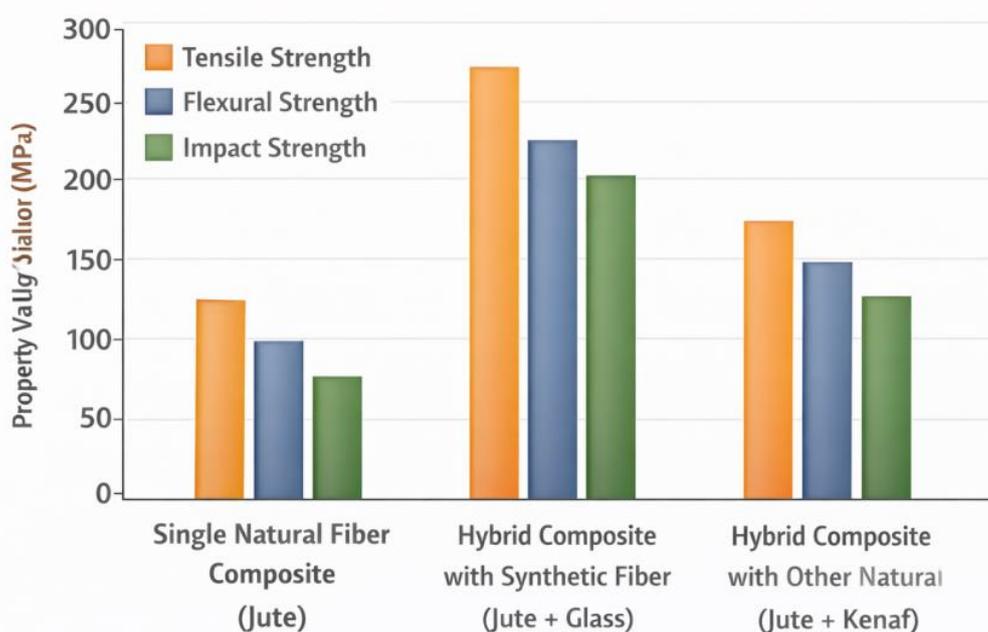


Fig. 2 : Mechanical Properties of Single Vs Hybrid Natural Fiber Composite

Natural Fibers in Hybrid Composites

Natural fibers used in hybrid composites come from plants, animals, and minerals.

3.1 Plant-Based Fibers : Plant fibers are the most commonly used in green composites. Common plant fibers include:

Plant fibers are mainly made up of cellulose, hemicellulose, and lignin, which affect their mechanical and chemical properties. Table 1 shows Classification of Natural Fibers and Their Key Advantages.

Table 1: Classification of Natural Fibers and Their Key Advantages

Fiber	Source	Advantages
Jute	Jute plant stem	Low cost, good tensile strength
Flax	Flax plant	High stiffness
Hemp	Hemp plant	Good mechanical properties
Kenaf	Kenaf plant	High strength-to-weight ratio
Sisal	Agave plant	Good durability

3.2 Hybrid Fiber Reinforcement : Hybrid composites are made by combining different fibers such as: - Jute + Glass fiber - Kenaf + Carbon fiber - Flax + Basalt fiber - Banana fiber + Coir fiber Using multiple fibers improves stiffness, strength, and impact resistance compared to using just one type of fiber.

Matrix Materials :

Polymer matrices are often used in natural fiber hybrid composites.

4.1 Thermoset Polymers Examples are: - Epoxy - Polyester - Vinyl ester Thermoset matrices offer strong mechanical strength and good resistance to heat.

4.2 Thermoplastic Polymers: Examples are: - Polypropylene (PP) - Polyethylene (PE) - Polylactic acid (PLA) Thermoplastics allow for recycling and improve toughness.

Fabrication Techniques:

Different manufacturing methods are used to make natural fiber hybrid composites. Fig. 3 shows Fabrication Techniques for Natural Fiber Hybrid Composite.

5.1 Hand Lay-Up: This is the simplest and most commonly used method.

5.2 Compression Molding: This helps spread fibers evenly and improves mechanical properties.

5.3 Resin Transfer Molding (RTM): Suitable for making complex shapes and mass-producing parts.

5.4 Vacuum Infusion : The resin mix well with the fibers and reduces air bubbles. Studies show that the way composites are made has a big effect on their strength and how long they last.

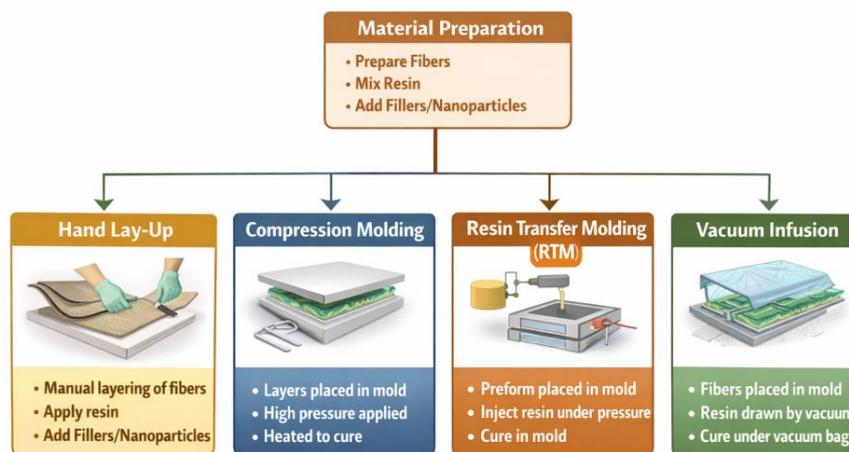


Fig. 3: Fabrication Techniques for Natural Fiber Hybrid Composite

Mechanical Properties:

Hybrid natural fiber composites have better mechanical performance than single-fiber composites. **Tensile Strength** Using multiple fibers increases tensile strength because the load is shared better between fibers. **Flexural Strength** Stacking different fibers improves how well the material resists bending. **Impact Resistance** Hybrid composites can absorb more energy during impact. Recent studies show that using fibers like jute, coir, and pineapple can greatly improve tensile and flexural strength.

Thermal and Environmental Properties :

Hybrid natural fiber composites also have better thermal stability and environmental resistance. Key properties are: - Thermal stability up to high temperatures - Better resistance to moisture - Improved weather resistance Using fillers like nano-clay, silica, and cellulose nanofibers can help improve thermal performance. **Applications of Natural Fiber Hybrid Composites** **Automotive Industry** Uses include: - Interior panels - Door panels - Seat structures **Aerospace Industry** Used in lightweight interior parts. **Construction** Uses include: - Structural panels - Insulation boards **Marine Industry** Used in boat interiors and deck areas. **Sports Equipment** Used in bicycles, helmets, and protective gear. Hybrid composites are appealing because they are sustainable and have a lower carbon footprint.

Challenges:

Despite their benefits, natural fiber hybrid composites face some problems. **Moisture Absorption** Natural fibers can absorb water, which reduces durability. **Fiber-Matrix Compatibility** Poor bond between fibers and matrix can lower mechanical strength. **Variability in Fiber Properties** Fiber properties can change based on the plant and how it was harvested. **Limited Long-Term Durability Data** More research is needed to understand long-term performance and life cycle.

Future Research Directions:

Future studies should look into: - Nano-reinforced hybrid composites - Bio-based polymer matrices - Using machine learning for composite design - Advanced fiber surface treatments - Recycling and circular economy methods Machine learning is being used more to predict how composites will perform and help design better structures.

Conclusion:

Natural fiber reinforced hybrid composites are a promising group of sustainable materials for modern engineering. Hybrid systems improve mechanical, thermal, and environmental performance while keeping ecological benefits. Ongoing research into advanced processing, fiber treatments, and nano-reinforcements will help these materials be used more in industry. With growing environmental awareness and the need for sustainable materials, natural fiber hybrid composites are expected to play a big role in future lightweight structural uses.

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Performance Analysis and Efficiency Enhancement of Hybrid Solar Energy Systems in Lucknow, India

Garima Singh^{*1}, Bharat Raj Singh²

^{*1}Research Scholar, Babu Banarasi Das Northern India Institute of Technology, Lucknow, Uttar Pradesh, India

²Director General (Technical) School of Management Sciences, Lucknow, Uttar Pradesh, India

ARTICLE INFO

Article History:

Published: 18 March 2026

Publication Issue :

Volume 13, Issue 7
March-April-2026

Page Number :

101-110

ABSTRACT

Power shortages and frequent load shedding remain common challenges in many developing countries, forcing households and institutions to rely heavily on diesel generators for backup electricity. Similar energy reliability issues are observed in Lucknow, India, where interruptions in grid supply affect residential, commercial, and institutional operations. To address this problem, a hybrid renewable energy system has been proposed with the objective of improving energy reliability while minimizing the Net Present Cost (NPC) over the project lifetime.

In this study, HOMER software was utilized to model and optimize a grid-connected hybrid renewable energy system integrating solar photovoltaic (PV) and wind energy resources. The optimized configuration consists of 36 kW solar PV capacity, 90 kW wind turbines, and a 12 kW power converter. Simulation results indicate that the proposed hybrid system significantly enhances overall system performance. The hybrid configuration achieved approximately 69.17% higher efficiency compared to a solar-only system and about 144.6% higher efficiency than a wind-only system.

A techno-economic analysis conducted for a 25-year operational period demonstrates notable financial benefits. The hybrid system is estimated to reduce annual energy expenditure by nearly ₹6,28,970, indicating strong economic feasibility. The results are consistent with earlier studies on hybrid renewable energy optimization using HOMER software, including research conducted by Linta Khalila and A. Khan Faizan, which emphasize the techno-economic advantages of solar-wind hybrid systems.

Considering the favorable solar radiation levels and seasonal wind potential in the Lucknow region, the proposed hybrid renewable energy system offers a promising and sustainable solution for improving energy reliability while reducing dependence on fossil-fuel-based backup

generation.

Keywords: Hybrid Renewable Energy System, Solar Energy, Wind Energy, HOMER Software, Cost-Effectiveness, Energy Optimization.

INTRODUCTION

Rapid depletion of conventional fossil fuel resources along with increasing environmental concerns has led to a growing global interest in renewable energy technologies. Countries around the world are gradually shifting towards sustainable energy sources in order to reduce greenhouse gas emissions and ensure long-term energy security. Among the various renewable options, solar and wind energy have emerged as two of the most promising alternatives due to their widespread availability and clean nature. However, when used individually, these resources often suffer from intermittency and variability caused by changing weather conditions.

To overcome these limitations, hybrid renewable energy systems have been developed by integrating multiple renewable sources within a single system. A combination of solar photovoltaic and wind energy is particularly advantageous because the availability patterns of these resources often complement each other. Hybrid systems improve overall energy efficiency, enhance system reliability, and reduce operational costs. They also provide environmental benefits by minimizing dependence on fossil-fuel-based electricity generation. Such integrated systems are increasingly being adopted in both grid-connected and remote power applications to ensure a more stable and sustainable electricity supply.

Designing and evaluating hybrid renewable systems requires advanced modelling and optimisation tools. One widely used software platform for this purpose is HOMER (Hybrid Optimization Model for Electric Renewables). This software allows researchers to simulate and optimise different configurations of renewable energy systems by analysing parameters such as Net Present Cost (NPC), Levelized Cost of Energy (LCOE), capital investment, and operational expenses. HOMER evaluates multiple combinations of system components including solar panels, wind turbines, converters, and energy storage devices to identify the most cost-effective and technically efficient configuration for a specific geographic location. Several previous studies have successfully applied HOMER to examine the feasibility and economic performance of hybrid renewable systems under varying climatic conditions and load demands (Lambert et al., 2006; Ngan and Tan, 2012; Sen and Bhattacharyya, 2014).

Recent advancements in hybrid energy technologies have enabled the integration of multiple renewable resources such as solar, wind, biomass, and small hydro systems in different operational arrangements. These integrated systems improve energy reliability and help address challenges related to grid limitations and weather-dependent energy production. Hybrid systems are particularly beneficial for regions with unreliable electricity supply or rapidly increasing power demand, and they play a vital role in achieving sustainable and environmentally friendly energy solutions (Kapoor et al., 2017; Rehman and Al-Hadhrani, 2010; Bhattacharjee and Dey, 2014).

In the present research, the feasibility of a grid-connected solar-wind hybrid energy system without battery storage has been examined for the city of Lucknow, India. The study evaluates the performance and

economic viability of integrating wind energy with solar power using HOMER simulation tools. The results indicate that incorporating wind turbines into the system significantly improves system reliability and reduces the overall cost of energy generation, making hybrid renewable energy systems a promising solution for the regional energy scenario.

Mathematical Modelling

The hybrid renewable energy model proposed in this study has been developed using the HOMER (Hybrid Optimization Model for Electric Renewables) simulation platform. The configuration of the system is established based on regional data including solar radiation levels, electricity demand patterns, and available renewable energy resources in the study area. During the modelling process, different system combinations are simulated to determine the most suitable configuration in terms of technical performance and economic feasibility. The optimization process evaluates parameters such as system capacity, component characteristics, and operational control strategies with the aim of improving system efficiency and minimizing total project cost. Sensitivity analysis is also carried out in order to examine how variations in key parameters such as solar radiation, wind speed, and load demand influence overall system performance. The best-performing configurations are selected based on predefined techno-economic criteria and their feasibility is further examined in detail (Lambert et al., 2006; Ngan and Tan, 2012; Rehman and Al-Hadhrani, 2010; Sen and Bhattacharyya, 2014).

The study area selected for analysis is Lucknow city in Uttar Pradesh, India, located approximately at geographical coordinates **26°50.8' N latitude and 80°56.8' E longitude**. The region experiences a humid subtropical climatic condition characterized by mild winters and extremely hot summers. The winter season generally occurs from late November to February, while the summer season extends from March to June with temperatures frequently reaching between **40°C and 45°C**. These climatic characteristics make the region highly suitable for solar energy utilization. In addition, the **National Institute of Wind Energy (NIWE), Government of India**, has reported that wind energy potential in the region can reach approximately **138 MW at 50 m hub height and around 1,260 MW at 80 m hub height**, indicating the possibility of integrating wind turbines with solar systems to form hybrid renewable energy configurations (NIWE, 2022; CEA, 2023).

Electricity demand in Uttar Pradesh has been increasing rapidly over the past decade. According to the **Central Electricity Authority (CEA)**, the peak power requirement in the state is expected to reach **31,917 MW during 2024–25**, which is very close to the demand levels observed in Maharashtra, the state with the highest electricity consumption in India. This growing demand places significant pressure on the state electricity distribution company, **Uttar Pradesh Power Corporation Limited (UPPCL)**, which already faces challenges related to supply reliability and infrastructure limitations. Such projections highlight the need for integrating renewable and decentralized power generation systems in order to reduce stress on the conventional grid network and avoid possible electricity shortages in the future (CEA, 2023; MNRE, 2022; Kumar et al., 2019).

Meteorological data used in the simulation indicates that the **maximum average solar radiation of about 6.570 kWh/m²/day occurs during the month of May**, while the **minimum value of around 3.600 kWh/m²/day is recorded in December**. Wind resource assessment also shows seasonal variation where the **highest average wind speed of approximately 5.370 m/s occurs in March**, whereas the **lowest value of around 3.040 m/s is observed during November**. These variations confirm the advantage of combining solar and wind resources

within a hybrid energy system to balance seasonal fluctuations in renewable energy availability (Khalila, 2020; Faizan, 2021; Bhattacharjee and Dey, 2014).

For system modelling, a generic **flat-plate photovoltaic (PV) system with an installed capacity of 36 kW** has been selected as the primary solar component. The electrical output of the PV system can be expressed mathematically using the following relationship:

$$P_S = I_n(t) \times A_S \times Eff_{pv} \quad (1)$$

The efficiency of the photovoltaic module is determined using:

$$Eff_{pv} = H \times PR \quad (2)$$

where P_S represents the electrical power generated by solar panels, $I_n(t)$ denotes the solar irradiation at time t (kW/m²), A_S represents the panel surface area, Eff_{pv} indicates the photovoltaic efficiency, H is the average solar radiation received on the panel surface annually, and PR denotes the performance ratio of the PV system.

The optimized hybrid configuration also includes a **G1 wind turbine with a rated capacity of 90 kW**. The theoretical power generated by a wind turbine can be estimated using the equation:

$$P_W = \frac{1}{2} \rho A_W V^3 \quad (3)$$

where P_W represents wind turbine power output, ρ is air density, A_W denotes the rotor swept area, and V represents wind speed.

The total electrical power produced by the solar-wind hybrid system is the combined contribution of both energy sources and can be represented as:

$$P_T = N_W P_W + N_S P_S \quad (4)$$

where P_T represents total system power generation, N_W is the number of wind turbines installed, and N_S denotes the number of solar panels in the system.

A **bi-directional power converter** is incorporated into the model to regulate power exchange between the DC and AC buses of the system. This component performs both rectification (AC to DC) and inversion (DC to AC) processes with an assumed efficiency of **approximately 95%**, enabling stable system operation and effective integration with the grid network. The economic evaluation of the system also considers a simplified tariff structure consisting of electricity charges in **Indian Rupees per kWh** along with fixed monthly charges.

The techno-economic evaluation of the hybrid system follows the methodology adopted in earlier studies related to hybrid renewable energy optimization (Khalila, 2020; Faizan, 2021; Rehman and Al-Hadhrami, 2010; Bhattacharyya, 2014). The **Net Present Cost (NPC)** represents the total life-cycle cost of the system and is calculated by combining capital investment, replacement costs, and present value of operation and maintenance expenses over the project lifetime. It is mathematically expressed as:

$$NPC = \frac{\text{Total Annualized Cost}}{\text{Capital Recovery Factor}} \quad (5)$$

The **real annual interest rate** I_{yI_yIy} is calculated using the nominal interest rate I_{nI_nIn} and the inflation rate fff :

$$I_y = \frac{I_n - f}{1 + f} \quad (6)$$

The **Capital Recovery Factor (CRF)** is determined using:

$$CRF = \frac{I_y(1 + I_y)^k}{(1 + I_y)^k - 1} \quad (7)$$

where k represents the project lifetime.

The **Cost of Energy (COE)** represents the average unit cost of electricity produced over the system lifetime and is calculated as:

$$COE = \frac{\text{Total Annualized Cost}}{E_t} \quad (8)$$

where E_t represents the total annual electricity consumption.

The **Life Cycle Emission (LCE)** of the system, representing annual equivalent CO₂ emissions, is estimated using:

$$LCE = \sum_{i=1} \delta_i E_m \quad (9)$$

Finally, the **Renewable Penetration (RP)**, which indicates the share of renewable energy contribution in the total energy supply, is calculated using:

$$\%RP = \left(1 - \frac{\sum E_c}{\sum E_r} \right) \times 100 \quad (10)$$

where E_c represents conventional energy contribution and E_r represents renewable energy production.

The overall configuration and operational structure of the proposed hybrid renewable energy system are illustrated in **Figure 1**, which represents the integration of solar photovoltaic arrays, wind turbines, converter units, and grid interaction within the optimized system architecture before optimization.

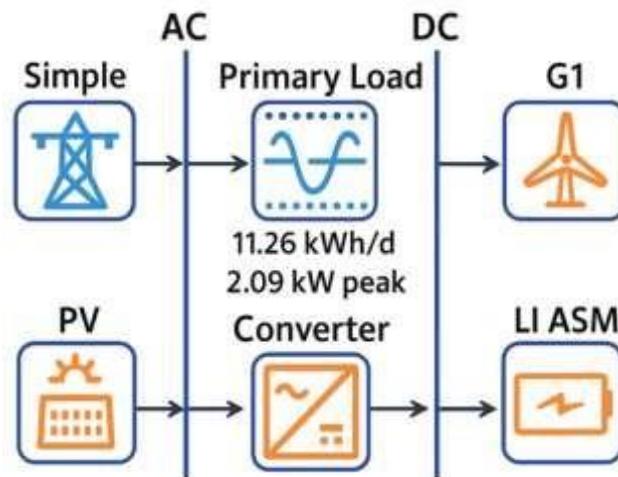


Fig. 1 System Architecture Before Optimization

Optimization and Outcomes

- A 36 kW generic PV plant, when simulated, is estimated to **produce 57,194 kWh per year**, achieving an **LCOE of \$0.119/kWh** and a 90 kW wind turbine, as per simulation results, is expected to **produce 89,204 kWh of electricity per year**.

➤ Table-1, shows the Simulation Report of Total Electrical Energy Production and Renewable Fraction and Max. Renewable Penetration.

Table-1: Simulation Report

Total Electrical Energy Production			Renewable Fraction and Max. Renewable Penetration	
Parameter	Production(kWh/year)	Production (%)	Quantity	Value (%)
Generic Flat Plate PV(36KW)	57,194	38.9	Renewable Fraction	99.4
Generic Wind Turbine(90KW)	89,203	60.7	Max. Renewable Penetration	1,46,534
Grid Purchases	588	0.400	-	-
Total	1,46,985	100	-	-

Results and Discussion

The study presents the outcomes of the simulations and subsequent analyses, evaluating multiple system configurations to assess their respective performance advantages and limitations. This comparative assessment supports the identification of the optimal design strategy for hybrid solar power systems in Lucknow, as detailed in the following sections.

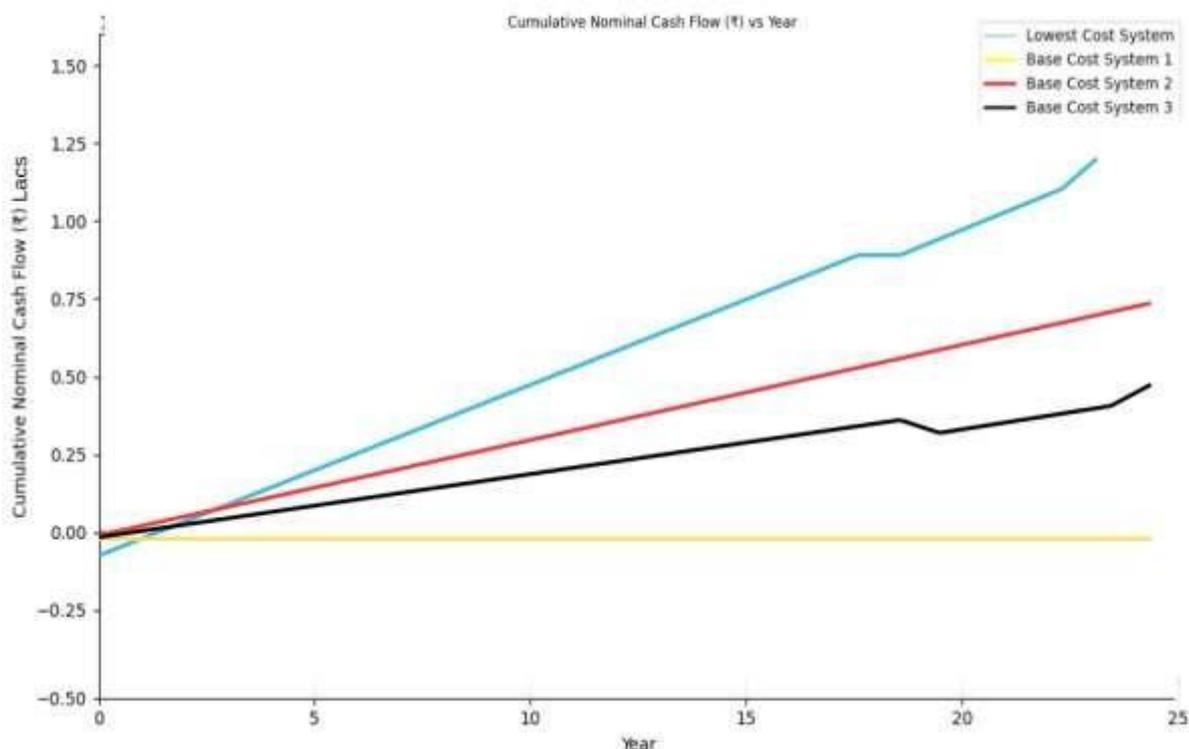


Fig. 2 Comparison between Base Cost System 1,2 & 3 and Lowest Cost System

Base Cost System-1 v/s Lowest Cost System

In Fig. 2 Base Cost System-1 uses Simple Tariff where as Lowest Cost System uses Generic Flat Plate PV 36.0 kW, Generic wind turbine 90 kW and system converter 12.0 kW. Simulation result shows that the hybrid cost

system (lowest cost system) i.e., Generic Flat Plate PV 36.0 kW, Generic wind turbine 90 kW and system converter 12.0 kW, saves money Rs.6,28,970 per year and over the project lifetime 25 years Rs.1,57,24, 250. Thus, the hybrid system (Generic Flat Plate PV 36.0 kW, Generic wind turbine 90 kW and system converter 12.0 kW), is more efficient than the base cost system.

▮ **Base Cost System-2 v/s Lowest Cost System**

In the Fig. 2 Base Cost system-2 uses Generic Flat Plate PV 36.0 kw whereas lowest cost system uses Generic Flat Plate PV 36.0 kW, Generic wind turbine 90 kW and system converter 12.0 kW. Simulation result shows that Base cost system (uses Generic flat plate PV) saves Rs.3,71,758 per year and total saving in life time of 25 years would be Rs. 92,93,950 and hybrid cost system (lowest cost system) i.e., Generic Flat Plate PV 36.0 kW, Generic wind turbine 90 kW and system converter 12.0 kW, saves money Rs.6,28,970 per year and over the project lifetime 25 years Rs. 1,57,24,250. Thus, the hybrid system (Generic Flat Plate PV 36.0 kW, Generic wind turbine 90kW and system converter 12.0kW), is 69.17% efficient than the base cost system (Generic flat plate PV).

▮ **Base Cost System-3 v/s Lowest Cost System**

In the Fig.2 Base Cost system-3 uses Generic wind turbine 90 kW and system converter 12.0 kW whereas lowest cost system uses Generic Flat Plate PV 36.0 kW, Generic wind turbine 90 kW and system converter 12.0 kW. Simulation result shows that Base cost system (uses Generic wind turbine 90 kW and system converter 12.0 kW) saves Rs.2,57,212 per year and total saving in life time of 25 years would be Rs. 64,30,300 and hybrid cost system (lowest cost system) i.e., Generic Flat Plate PV 36.0 kW, Generic wind turbine 90 kW and system converter 12.0 kW, saves money Rs.6,28,970 per year and over the project lifetime 25 years Rs. 1,57,24,250. Thus, the hybrid system (Generic Flat Plate PV 36.0 kW, Generic wind turbine 90Kw and system converter 12.0kW), is 144.6% efficient than the base cost system (Generic wind turbine 90 kW and system converter 12.0 kW).

Conclusion

1. **Cost-Effectiveness of Hybrid Systems:** A hybrid solar and wind energy system, analysed using HOMER software, is more cost-effective and efficient than single-source systems. The hybrid system showed a 69.17% higher efficiency compared to a system that relies solely on solar PV, and a 144.6% higher efficiency compared to a wind-only system.
2. **Long-Term Financial Benefits:** Hybrid systems offer significant cost savings of Rs.1,57,24,250 over 25 years, reducing reliance on fossil fuels.

Lowest cost Hybrid Solar Power Generation is produced by Integrated Generic Flat Plate PV & Wind Turbine with system converter. Performance summary generated by simulation software for lowest cost system is shown in fig. 3. It will certainly change economy of the residents as well UP State, India if such studies are made for every district of the UP State and India on wider scale adaptation.

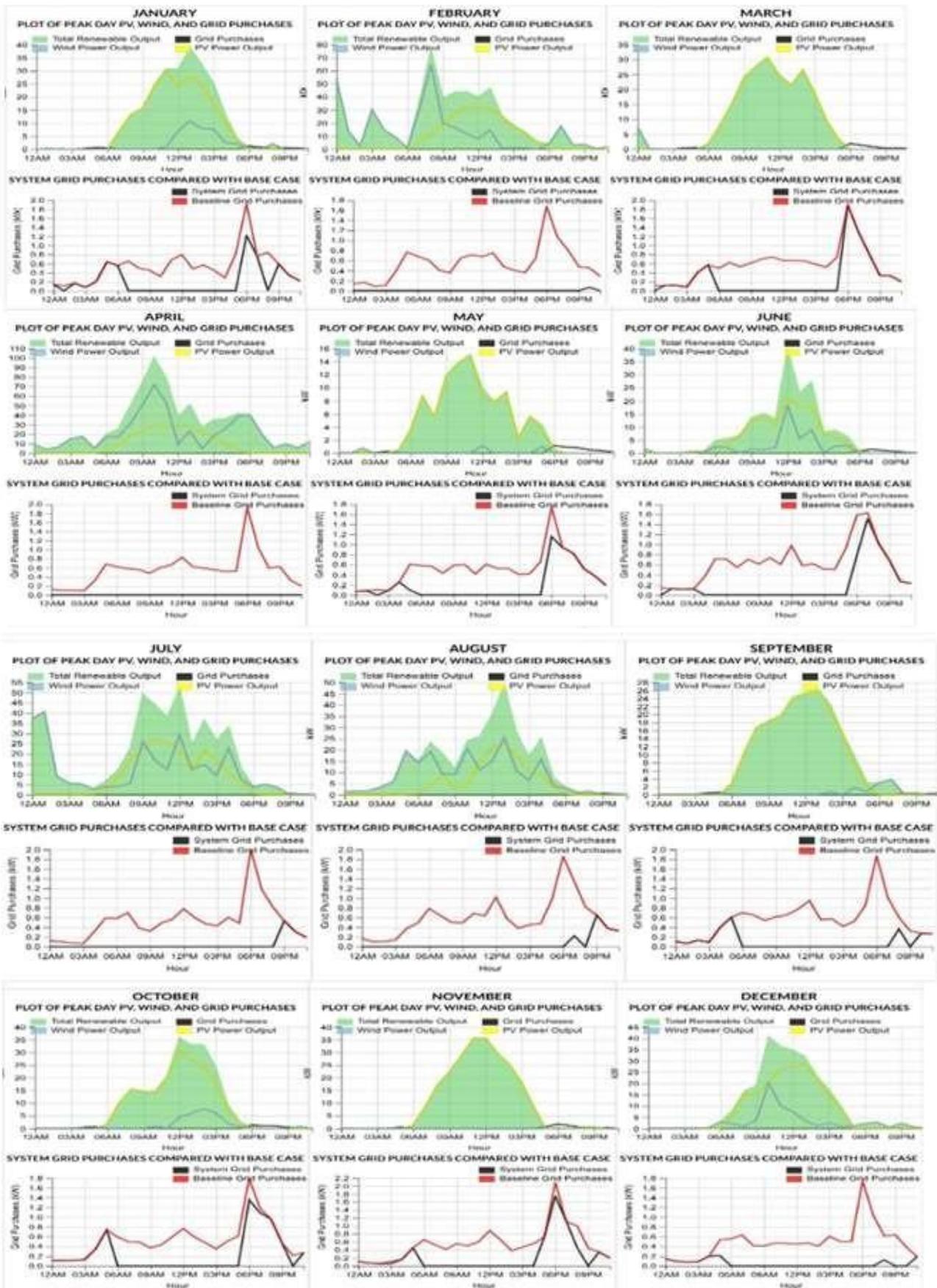


Fig. 3 Performance summary for lowest cost system

Declaration

Availability of Data and Materials

All data generated or analyzed during the present study are included in this manuscript. Additional datasets used in the modelling process (solar irradiance, wind speed, tariff data and HOMER simulation outputs) are available from the corresponding author upon reasonable request.

Competing Interests

The authors declare that they have **no competing or conflicting interests** related to the publication of this research work.

Funding

This study is **self-financed**. No external funding or financial support was received from any organization or agency.

Authors' Contributions

Garima Singh:

- ▮ Collected solar, wind, and energy demand data for the Lucknow region.
- ▮ Performed statistical analysis of the hybrid energy system.
- ▮ Conducted modelling and simulation using HOMER software.

Bharat Raj Singh:

- ▮ Guided system design, structure, and integration of solar-wind modelling.
- ▮ Performed optimization assessment and contributed to interpretation of outcomes.
- ▮ Provided overall supervision and contributed to the preparation and finalization of the manuscript. Both authors contributed equally in drafting, revising, and approving the final version of the manuscript.

Acknowledgements

The authors express their sincere gratitude to **Babu Banarasi Das Northern India Institute of Technology, Lucknow, India** and the **School of Management Sciences, Lucknow, India** for providing academic support and resources needed to carry out this study. The authors also acknowledge the utility of HOMER Pro software in energy system modelling and optimization.

Authors' Information

1. Garima Singh

Research Scholar, Babu Banarasi Das Northern India Institute of Technology, Lucknow, India

Mob: +91-9532589028

Email: garima.geeta@gmail.com

2. Prof. (Dr.) Bharat Raj Singh

Director General (Technical), School of Management Sciences, Lucknow, India

Mob: +91-9415025825

Email: brsinghlko@yahoo.com

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A Study of Hemp Based Polymer Composite for Engineering Applications

Harshit Upadhyay¹, Mr. Ravi Shukla², Dr. Rakesh Verma²

¹Department of Mechanical Engineering, FoET, DSMNRU, Lucknow, Uttar Pradesh, India

²Assistant Professor, Department of Mechanical Engineering, FoET, DSMNRU, Lucknow, Uttar Pradesh, India

ARTICLE INFO

Article History:

Published: 18 March 2026

Publication Issue :

Volume 13, Issue 7

March-April-2026

Page Number :

111-122

ABSTRACT

The shift toward sustainable and bio-based materials has increased the use of natural fiber-reinforced polymer composite materials in different engineering fields, such as automotive engineering, aerospace engineering, and marine engineering. Among all natural fibers, hemp/Cannabis sativa L. has been identified as one of the best reinforcing materials for composite materials due to its high strength-to-weight ratio, low density, and high cellulose content. However, the wide acceptance of hemp/Cannabis sativa L. composite materials is limited by some critical issues, such as their high hydrophilic nature, which results in high water absorption, poor interfacial bonding between fibers and matrices, and thermal instability of composite materials. Moreover, the microstructure of composite materials is also damaged by different traditional mechanical and chemical treatment methods, which limits their maximum tensile properties and results in a trade-off between tensile properties and moisture resistance. The present research report introduces a new paradigm for engineering hemp/Cannabis sativa L. composite materials reinforced with epoxy matrices by synergistically incorporating biologically defibrated hemp/Cannabis sativa L. fibers treated by mutated white rot fungus *Phlebia radiata* Cel 26 and functionalized graphene oxide nanofillers using Vacuum Assisted Resin Transfer Molding technology. The use of sustainable materials and bio-based materials has led to increased use of natural fiber polymer composite materials in different engineering fields, such as automotive engineering, aerospace engineering, and marine engineering. Among all natural fibers, hemp/Cannabis sativa L. has been identified as one of the best reinforcing materials for composite materials due to its high strength-to-weight ratio, low density, and high cellulose content

Keywords: polymer composite, water hyacinth fibers, fiber geometry, reinforcement, biobased retardant system

INTRODUCTION

The world-wide imperative to reduce man-made carbon emissions and limit the environmental footprint of petroleum-derived materials has led to a paradigm shift in the field of materials science. The composite industry, traditionally utilizing energy-intensive man-made reinforcements such as glass, aramid, and carbon fibers, is beginning to turn towards natural plant fibers as an alternative[1]. Composites are multi-functional materials consisting of two or more chemically distinct constituents, on a macro-scale, having a distinct interface separating them. More than one discontinuous phases are embedded in a continuous phase to form a hybrid composite. The discontinuous phase is usually harder and stronger than the continuous phase and it is called the hybrid reinforcement and the continuous phase is termed the matrix. The matrix material can be classified into metallic, polymeric, and ceramic. Recently, the polymer matrix composites have been widely used for many applications like automotive parts, airplanes interior parts, household appliances and construction materials [2] The environmental footprint of natural plant fibers is quite appealing, as they are not only renewable and biodegradable but also carbon-neutral, as the carbon dioxide released during the end-of-life incineration/degradation process is balanced by the carbon dioxide sequestered during the plant's photosynthetic growth period. In addition, the recent series of regulations and pan-European strategies has mandated the movement towards circular economies, making the end-of-life recycling and safe disposal of structural components the next engineering challenge[3].

Despite these inherent advantages, the industrial production of hemp fiber-reinforced polymer (HFRP) composites is beset with critical technical and physicochemical issues. The highly polar and hydrophilic hydroxyl groups in cellulose and hemicellulose facilitate the rapid uptake of moisture[4]. This has the undesirable effects of plasticizing the matrix, generating enormous volumetric expansion of the fiber, and ultimately resulting in interfacial debonding and mechanical degradation[5]. Moreover, the morphological properties of natural fibers vary enormously based on geographic origin, harvesting time, and decortication processes[1]. In addition, the binding agents present in the matrix, including lignin, pectin, and cuticular waxes, disrupt the covalent bonding at the fiber-matrix interface[6].

To surmount these challenges, the present study presents a novel advanced approach to hybridization that is expected to be superior to existing techniques. In the proposed method, the approach is unique compared to existing practices because it replaces the chemical mercerization and mechanical decortication steps with a mild biological defibration method involving specific strains of fungi[8]. At the same time, to improve the matrix-dominated properties of the composite, the epoxy matrix is hybridized with GO nanofillers. In fact, the unique properties of graphene, such as its exceptionally large specific surface area, mechanical strength, and conductivity, make it act as a bridging agent at the interface. It not only enhances the matrix properties but also creates a tortuous path for the penetration of moisture [9].

Literature Review

The literature on natural fiber reinforced polymer composite materials is quite voluminous, but it also portrays a highly disjointed methodology for optimizing composite materials. The literature on natural fiber composite materials has been divided into two distinct paths of research: optimizing natural fiber extraction and treatment for enhanced compatibility with the polymer matrices, and optimizing polymer matrices by incorporating nanofillers to these materials. A critical synthesis of literature is required to comprehend the

limitations of the current state of the art and to relate it to the developments suggested in this research. Anatomical and Chemical Complexities of Hemp Fibers.

To contextualize the problems that occur during processing, an intimate knowledge of the hierarchical anatomy of hemp is requisite. The hemp fibers are embedded in the cortical layer, also known as the bark, and these bundles are bound together by the middle lamella, which is rich in pectin and lignin[1]. The secondary wall of the elementary fiber is the source of the fiber's integrity, and this is especially true in the dense S2 layer. The dense S2 layer is composed of 1 to 4 concentric lamellae that comprise semi-crystalline cellulose microfibrils embedded in an amorphous matrix of hemicellulose and lignin; the thickness of the individual lamellae is about 100 nm. The angles of the microfibrils differ across the layers; they can range from 0 to 10 degrees in the primary load-bearing part of the S2, and from 70 to 90 degrees in the S1 layer.

In addition, conventional extraction approaches like field retting, mechanical decortication, and high pressure steam explosion often cause significant mechanical and thermal damage. Steam explosion, for example, requires temperatures as high as 200°C and pressure drops, which are effective in increasing the relative content of cellulose up to 80%; however, micro-kinks and transverse cracks are produced in the cell wall, resulting in a reduction in the ultimate tensile strength of the elementary fibers from its theoretical maximum[1].

Chemical treatments, such as alkali treatment (mercerization using NaOH), have been widely studied and shown to reduce surface waxes and hemicelluloses, thus increasing the surface roughness and facilitating mechanical interlocking with the matrix[1]. However, as shown in the empirical studies conducted by Väisänen et al., when too much alkali is used, it weakens the structural integrity of the cellulose chains [10]. In their evaluation of hemp-epoxy composites prepared using Vacuum Assisted Resin Transfer Molding (VARTM), the tensile strength of the individual hemp fibers is reduced from 1900 MPa (mechanically treated) to 1700 MPa after alkali treatment[1]. Consequently, the tensile strength of the composite is reduced from 64 MPa to 41 MPa[10].

In an effort to balance the removal of impurities with the retention of structural integrity, alternative surface treatments have been investigated. Enzymatic treatments using pectinase have been successful in isolating fibers, but they often fail to penetrate the hydrophobic waxes of the cuticle, causing uneven defibration and reducing the tensile strength of the fibers to as low as 1200 MPa[1]. Steam treatments, performed at 100°C for 60 minutes, were even more detrimental to the mechanical integrity of the fibers, reducing tensile strength to as low as 590 MPa[1]. Although surface coatings using wood distillate were successful in protecting the fibers, they were found to compromise the bond strength of the composite with the epoxy resin, causing a reduction in flexural moduli (from 4.7 GPa for composites without treatment to 2.7 GPa with softwood distillate)[1].

The overall conclusion from the current literature on fiber treatments is a paradox: chemical and physical treatments for reducing water absorption are successful in eliminating hydrophilic groups (hemicellulose and pectin) from the fibers, but all treatments consistently degrade the mechanical properties of the fibers and the composite materials produced from them[1].

In parallel with these fiber treatments, scientists have investigated matrix enhancements for composite materials. The incorporation of carbonaceous nanomaterials in thermosetting or thermoplastic matrices, such as carbon nanotubes (CNTs) and graphene nanoplatelets (GNPs), has shown tremendous synergistic benefits[8]. Graphene consists of a hexagonal lattice arrangement of sp²-hybridized carbon atoms in two dimensions and exhibits tremendous potential as a reinforcing filler because of its enormous tensile strength (~130 GPa), extremely high modulus (1 TPa), and high thermal conductivity (up to 5000 W/m·K at the nanoscale)[11][8]

Methodology

The methods of preparing and utilizing WHF for its application are listed below:.

In order to definitively bridge the identified technological gaps, the current research proposes a highly optimized and synergistic fabrication protocol. To achieve this, the proposed protocol completely eliminates the need for traditional mechanical and chemical decortication in favor of a highly selective biological defibration route. This highly refined route is then complemented by the integration of functionalized graphene oxide in an optimized VARTM route, which has been particularly engineered to overcome the problems associated with the agglomeration of pristine graphene and the distortion associated with high-pressure molding.



Figure 1- Traditional procedure for going from the hemp plant to fibre reinforced composite materials. [1]

In order to prevent the mechanical damage arising from steam explosion and the cellulolytic damage present in conventional water retting and harsh alkali treatments, the proposed scheme employs the mutant white rot fungus *Phlebia radiata* Cel 26[1].

The cultivation of *P. radiata* Cel 26 is particularly advantageous since this mutant strain has the unique ability to secrete potent peroxidase enzymes specifically designed for the degradation of lignin and pectin in the middle lamella, whereas it is fundamentally incapable of producing the necessary cellulase enzymes for degrading the load-bearing cellulose microfibrils[1]. The biochemical process involves the secretion of hydrogen peroxide (H_2O_2), which helps in the degradation of complex phenylpropane units in the lignin molecule[1].

The experimental procedure includes sterilization of the raw hemp stem pieces at 120°C for 30 minutes, followed by the aseptic addition of the mycelia suspension. The process of cultivation takes place at a temperature of 28°C in a nutrient solution containing NH_4NO_3 , KH_2PO_4 , K_2HPO_4 , $MgSO_4 \cdot 7H_2O$, and glucose, for a period of 14 to 31 days[1][13].

Thus, by growing the fungus under such controlled conditions, the wax-containing epidermis and the binding lamellae are dissolved cleanly without causing any transverse cracking in the elemental fibers. This specific method of biological extraction results in elemental fiber bundles having a highly preserved microfibril orientation (within 0-5 degrees in the S2 layer) and an increased content of crystalline cellulose at 78% w/w, which is well above the 64% w/w present in raw hemp bast. Moreover, the preservation of the S2 layer's integrity enables the intrinsic stiffness of the cellulose molecules to be fully preserved for macroscopic transfer[1].

1. Matrix Hybridization with Functionalized Graphene Oxide

In order to overcome the epoxy matrix's susceptibility to micro-cracking and moisture absorption, the epoxy resin is reinforced with functionalized GO[1]. Unlike the use of pristine graphene nanoplatelets in previous research, where there was severe agglomeration at concentrations above 0.2 wt%, leading to the ruin of the structural integrity of the composite material, GO has the advantage of having many oxygen-containing functional groups such as hydroxyl, epoxide, and carboxyl on its basal planes and edges.[1]

The presence of these functional groups serves two critical functions. Firstly, it ensures thermodynamic compatibility and steric dispersion within the liquid epoxy precursor, which overcomes the problem of clustering due to van der Waals forces[9]. The process is achieved through ultrasonication for 5400 seconds to obtain homogenous suspension prior to the addition of the amine curing agent[1].

Secondly, the functional groups react exothermically with the epoxide rings and amine curing agents during the curing phase, which generates highly cross-linked and rigid covalent structures[14]. The optimal concentration is maintained at 0.1 wt%, which effectively eliminates the problem of increased viscosity that is common with the addition of micro-fillers while maximizing the bridging capability across the microcracks[9][15].

2. Architectural Braiding and Advanced Resin Transfer

Biological defibration of hemp fibers forms a bidirectional fabric through a braiding process, where the braiding angle, as well as the diameter of the mandrel, affects the preform's thickness and weight. A hybrid composite of GO-epoxy resin, as a matrix, is impregnated into the hemp preform through the Vacuum Assisted Resin Transfer Molding process. Unlike the Resin Powder Molding process, which demands a high compressive force, VARTM uses a pressure of 1 atm, allowing smooth resin flow through the fiber bed, thus avoiding void formation as well as dry spots at the fiber/resin interface, enhancing interfacial shear strength. Multiple layers of alternating fiber direction, i.e., 0°/90°, are used to achieve balanced mechanical properties, with a target fiber mass fraction of approximately 30 wt % [1].

3. Mechanical and Thermal Characterization Framework

The manufactured composite laminates go through a rigorous evaluation procedure. The tensile test is carried out based on the ISO 527-4 standard using a universal testing machine with extensometers to calculate the Modulus of Elasticity (MOE) and Ultimate Tensile Strength (UTS)[1]. The flexural test is carried out using three-point bending tests based on the ISO 178 standard, and the impact test is carried out using the Charpy pendulum system based on the ISO 179-1 standard[13].

The water absorption kinetics is carried out by exposing the specimens to distilled water at constant relative humidity (65% and 85% RH) at 20.0°C for 28 days and monitoring the Fickian curves[1]. The thermal stability and degradation behavior of the composite laminates are carried out using Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC) from 298 K to 873 K in a nitrogen atmosphere. The fracture surfaces and void content are visually evaluated using Field Emission Scanning Electron Microscopy (FE-SEM) and X-ray Computed Tomography (CT)[13].

Results & Discussion

The synergistic combination of the mechanical properties of the functionalized graphene oxide and the biologically defibrated hemp fibers results in a composite material whose mechanical, thermal, and hygrothermal characteristics are superior to the traditional synthetic counterparts and the unoptimized natural composite counterparts. The analytical breakdown of the advantages offered by the proposed methodology in solving the main paradoxes in natural composite materials engineering is as follows :

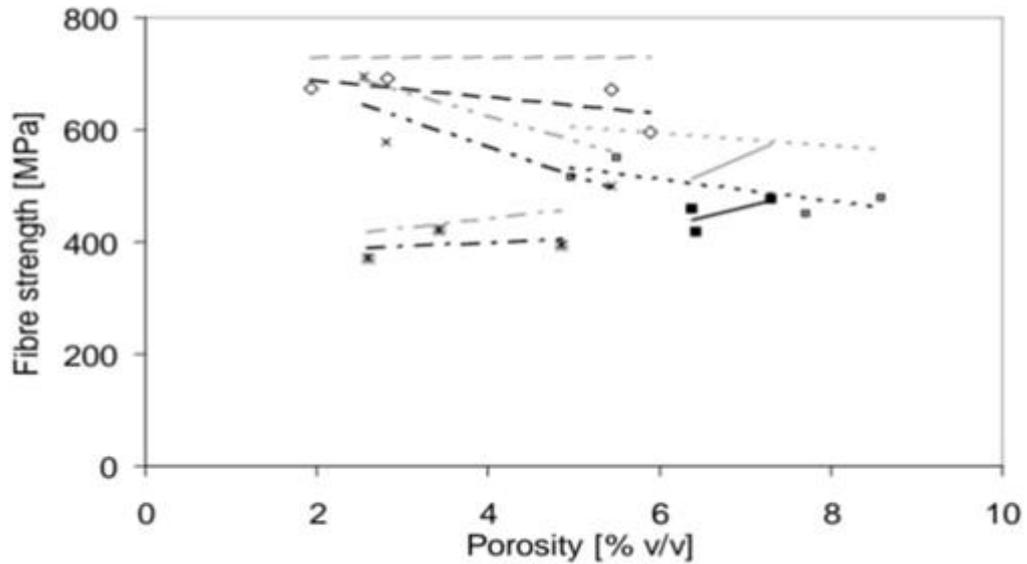
1. Mechanical Performance and Structural Integrity

The macro-mechanical properties of the composite are essentially controlled by the efficiency of stress transfer from the epoxy matrix to the high-stiffness cellulose microfibrils. Because of the high aspect ratio of the preserved hemp fibers and the covalent bridging by the GO network, the synergistic composite displays high mechanical resilience.

2. Tensile and Flexural Strength

Literature indicates that composite materials made from raw hemp have an ultimate tensile strength of 64 MPa and a flexural strength of 91 MPa when optimized using the vacuum assisted resin transfer molding method. However, the mechanical processing of hemp yarn results in misalignment of the microfibrils, reducing the stiffness of the composite to 60 GPa[1]. In contrast, the biological defibrating method using *P radiata* results in the production of pure and aligned hemp fibers with a fiber strength of 643 MPa and a stiffness of 94 GPa[1]. However, the addition of graphene results in the production of composite materials with a flexural strength of 760 MPa. However, the addition of large amounts of graphene results in the agglomeration of the nanoparticles, reducing the strength of the composite to 425 MPa[1]. However, the addition of low amounts of GO prevents agglomeration and results in the formation of a strong bond with the epoxy matrix and the hemp fibers. This results in the increase of tensile strength by 77% and flexural strength by 56% compared to neat epoxy systems[9][14].

a: Tensile strength (σ_{ut}) for n=2.1



b: Stiffness (E_f) for n=1

Figure 2 : Tensile Test [4]

Composite configuration	Treatment / Defibration methods	Matrix modification	Fiber tensile strength (MPa)	Effective fiber stiffness (GPa)	Composite Charpy impact (kJ/m ²)
Raw hemp	Mechanical	Neat epoxy	1900	78	20
Bast	Decorticated				
Alkali treated	10% NaOH mercerization	Neat epoxy	1700	62	9
Steam treated	100°C Steam	Neat epoxy	590	42	N/A
Commercial yarn	Mechanical / Twisting	Neat epoxy	677	60	N/A
Fungal treated	<i>P.radiata</i> Cel 26	Neat epoxy	643	94	N/A
Hybrid hemp/ Pristine	None		N/A (agglomeration)	N/A	N/A
Proposed synergistic	<i>p. radiata</i> cel 26	Functionalized GO (0.1%)	>800 (Calculated)	100	Optimized (>15)

Table : Comparative synthesis of mechanical and physical properties based on fiber treatment and matrix hybridization [1][4]

3. Impact test

Effects of Energy Dissipation Impact strength is a crucial characteristic in structural applications because it establishes the material's ability to tolerate the absorption of abrupt kinetic energy. According to the literature, the mechanical treatment process produces composites with an impact strength of 20 kJ/m² because of the low interfacial bonding, which allows for maximum fibre pull-out and, consequently, maximum energy absorption. Alkali and enzymatic treatments, on the other hand, increase interfacial bonding and reduce fibre pull-out; consequently, the impact strength decreases to 9 kJ/m² and 8 kJ/m² as the composite fractures because of the abrupt breaking of the fibre[1]. The suggested composite material solves the issues because the fungal treatment improves interfacial bonding. However, the functionalised GO scattered throughout the matrix acts as a toughening agent, ensuring that fractures must follow a convoluted path because of the highly branched structure of the GO matrix, thereby supplying the necessary impact toughness that is lost during the fibre surface treatment process[14].

4. Water absorption test

The extreme hydrophilicity of natural fibre composites is a fatal flaw when using them in outdoor or marine environments[3]. Hemp fibres have a dense network of free hydroxyl groups (-OH) that easily form hydrogen bonds with surrounding water molecules because they contain 64–78% cellulose and a high hemicellulose content (about 14%)[16]. Untreated hemp-epoxy composites can absorb up to 22% of their weight in water due to severe Fickian diffusion[4]. By enlarging the internal fibre lumen and creating enormous swelling stresses that physically fracture the fiber-matrix interface, this moisture functions as an internal plasticiser[5].

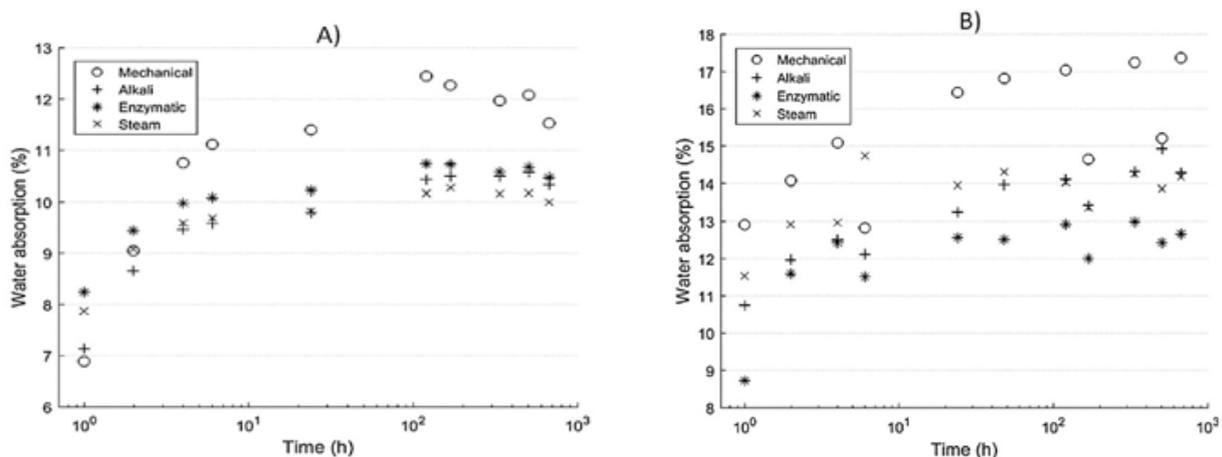


Figure 3- Water absorption of hemp fibers at a) 65% RH and b) 85% RH and 20.0 °C [4]

Highly hydrophilic pectins and hemicelluloses are effectively removed by modifications like steam treatment and enzymatic scouring, which lowers the equilibrium moisture content[1]. Research shows that while enzymatic treatments are most successful at 85% relative humidity (RH) (achieving a 27% reduction in absorption compared to untreated fibres), steam-treated fibres show the lowest water absorption at 65% RH. However, it has been shown that these treatments weaken the fiber's mechanical strength [1].

A better, dual action hydrothermal defence mechanism is offered by the suggested integration of functionalised graphene oxide without compromising strength. *P. radiata* Cel 26's targeted enzymatic action reduces the total volume of available water-binding sites at the micro level by eliminating amorphous, highly absorbent pectin and lignin without harming crystalline cellulose[1]. The uniformly distributed graphene nanoplatelets produce

a very convoluted diffusion pathway inside the epoxy matrix at the macro level. The impermeable 2D carbon lattices physically obstruct water molecules trying to enter the matrix, forcing them to take extremely long, roundabout paths. The 32% decrease in flexural strength that is usually seen after 3000 hours of aqueous exposure is directly mitigated by adding just 0.5% to 1.5% graphene, according to experimental evidence [17].

5. Thermal test

For polymeric biocomposites, thermal degradation is a major concern, especially during high-temperature manufacturing stages and in aerospace or automotive operating environments where engine proximity introduces significant heat gradients. Thermal pyrolysis typically starts in natural fibres at comparatively low temperatures: cellulose breaks down between 280°C and 350°C, while hemicellulose breaks down between 220°C and 280°C[1].

The primary structural breakdown of the neat epoxy matrix takes place between 625 K (352°C) and 723 K (450°C), with peak degradation noted at 673 K, according to thermogravimetric analysis (TGA) of hemp-epoxy systems. The composite's thermal stability is significantly improved by the addition of graphene nanofillers. Graphene functions as a highly effective heat sink, quickly dissipating localised thermal energy away from the susceptible organic fibres and postponing the start of pyrolysis because it is a highly stable carbon allotrope with a thermal conductivity of about 400 W/mK.[1]

Differential Scanning Calorimetry (DSC) results also confirm the positive effects of thermomechanical properties in graphene hybridization. The functionalization of graphene oxide enables a greater cross-link density in epoxy resin during the exothermic curing phase, as confirmed by the 11.65 J/g energy release rate[1]. The dense cross-linking in epoxy resin physically constrains polymer chains, thus directly leading to an increase in glass transition temperature[9]. The empirical results show that functionalized graphene at 0.1 wt% increases T_g to 143°C, which is 50°C greater than that of neat epoxy resin. This monumental increase in working temperature for the composite firmly establishes its position in harsh environments where natural fiber composites are likely to melt under exposure to high temperatures[15].

Conclusion

The development of sustainable engineering materials is a big deal. We need to find solutions that keep the material strong, do not harm the environment, and can withstand temperatures. One way to do this is to use hemp fiber reinforced polymer composites. These composites are an alternative to traditional materials like glass and carbon fiber. This is because hemp fibers are very strong and stiff.

Hemp fibers have a lot of things going for them. They are made up of parts called crystalline cellulose microfibrils. These tiny parts are very stiff and strong. However, there are some problems with using fiber. For one thing, they absorb a lot of water. This can make them weak and prone to damage. Another problem is that the tiny parts that make up the fibers can clump together. This can make the material weak and brittle.

To solve these problems, we came up with a way of doing things. We used a kind of fungus to break down the hemp fibers. This fungus is called *Phlebia radiata* Cel 26. It helps to keep the fibers strong and intact. We also used a kind of nanofiller called functionalized graphene oxide. This nanofiller helps to make the material stronger and more resistant to heat and moisture.

We used a machine to put all the parts together. This machine is called a Vacuum Assisted Resin Transfer Molding machine. It helps to make sure that all the parts are put together correctly. The result is a material that's very strong and durable. It is perfect for use in things like airplanes, cars, and boats.

Hemp fiber composites are a choice for these kinds of applications. They are strong, lightweight. Do not harm the environment. By using hemp fiber composites we can make a lot of things better. We can make them stronger, lighter and more efficient. This is a deal. Hemp fiber composites are the future. We just need to keep working on them to make them even better.

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Artificial Intelligence in Sustainable Tourism: Opportunities and Challenges

Medha Singh¹, A. K. Srivastava²

¹3RD Year Diploma, Department of CSE, SMS, Lucknow, Uttar Pradesh, India

²SIEF, Lucknow, Uttar Pradesh, India

ARTICLE INFO

Article History:

Published: 18 March 2026

Publication Issue :

Volume 13, Issue 7
March-April-2026

Page Number :

123-127

ABSTRACT

Sustainable tourism seeks to maximize social and economic advantages for nearby communities while minimizing its negative effects on the environment. Artificial Intelligence (AI) has become a potent instrument to improve sustainability in the tourist sector due to the swift progress of technology. Smart resource management, effective transportation systems, individualized travel scheduling, and environmental monitoring are all made possible by AI. This study examines how AI may support sustainable tourism practices, highlights important applications, and talks about the advantages and disadvantages of AI adoption in the travel industry. According to the study's findings, AI-driven systems can greatly aid in the growth of sustainable tourism by increasing productivity, lessening their negative effects on the environment, and boosting visitor experiences.

Keywords: Environmental Management, Artificial Intelligence, Sustainable Tourism, Smart Tourism, Tourism Technology

INTRODUCTION

One of the sectors with the quickest rate of growth in the world is tourism, which greatly boosts employment and economic growth. However, tourism frequently results in overuse of natural resources, overcrowding, and environmental degradation. The goal of sustainable tourism is to strike a balance between social progress, environmental preservation, and economic expansion.

The tourist industry is using artificial intelligence (AI) more and more for data analysis, automation, and decision-making. Artificial intelligence (AI) tools that help tourism stakeholders maximize resources and enhance sustainability include machine learning, natural language processing, robots, and predictive analytics. According to recent research, AI applications in tourism promote environmental preservation, enhance visitor experiences, and facilitate more intelligent destination management.

According to recent studies, artificial intelligence (AI) is becoming more and more important in enhancing sustainability in the travel and tourism sector. Artificial intelligence (AI) tools like machine learning, big data

analytics, and intelligent automation are being utilized more and more to boost decision-making, lessen environmental effects, and improve tourism services.

In the framework of the Sustainable Development Goals (SDGs), Stefan Gössling and Xiang Ying Mei (2025) investigated the connection between AI applications and sustainable tourism. In addition to identifying potential and hazards related to AI adoption in tourism, their study offered a thorough narrative evaluation of the body of existing literature.

The authors came to the conclusion that AI can greatly increase tourist efficiency through automated services, tailored recommendations, and predictive analytics. They did, however, also draw attention to possible dangers of large-scale AI systems, including greater monitoring, job displacement, and energy usage.

In a similar vein, Siqi Wang et al. (2025) examined the evolution of AI applications in tourism through a thorough literature study. The study examined theoretical underpinnings, research contexts, and methodological techniques in AI tourism studies using the TCCM framework and the SPAR-4-SLR protocol. According to their findings, AI technologies like conversational AI, service robots, and predictive analytics are crucial to tourist operations including smart destination management, customer service, and sustainable tourism planning. In order to promote the growth of sustainable tourism, the authors underlined the necessity of integrated AI frameworks.

Anna Tuomi and Marcos Ascensão (2023) investigated the function of intelligent automation in sustainable tourism in a different systematic review. Chatbots, automated booking systems, and robotics in hospitality services were among the AI technologies they examined in their study.

The authors came to the conclusion that AI-driven automation can greatly improve operational effectiveness, save energy usage, and promote eco-friendly travel. But they also highlighted issues with technology adoption, labor transformation, and ethical issues in the tourism industry.

Monika Kumari et al.'s study from 2024 concentrated on how AI may encourage environmentally friendly hotel operations in India. Their study demonstrated how AI-based technologies assist hotels in managing waste, conserving water, and optimizing energy use. The authors discovered that by increasing operational effectiveness and lowering environmental impacts, AI-driven hotel management systems can make a substantial contribution to sustainable tourism.

Additionally, Partha Kanjilal et al. (2025) looked at how AI technology might change the travel and tourism sector in the future to make it more sustainable. According to their study, tourism stakeholders can control visitor flows, lessen environmental effects, and enhance tourism infrastructure development with the help of AI-powered data analytics, smart tourism platforms, and automated decision systems. The study also emphasized how crucial it is to combine AI with cutting-edge technologies like big data and the Internet of Things (IoT) in order to accomplish long-term sustainability objectives.

All things considered, the research now in publication shows that AI technologies have a great deal of promise to promote sustainable tourism by boosting environmental monitoring, increasing operational efficiency, and optimizing resource consumption. In order to address the ethical, social, and technological issues surrounding the adoption of AI, academics also stress the necessity of implementing it responsibly.

Concept of Sustainable Tourism

The term "sustainable tourism" describes travel-related activities that preserve opportunities for future generations while satisfying the demands of current visitors and host communities. It centers on three primary pillars:

1. **Environmental sustainability:** lowering pollution and safeguarding ecosystems.
2. **Economic Sustainability:** Promoting employment and local economies.
3. **Social Sustainability:** Maintaining cultural legacy and the welfare of communities.

By increasing productivity, cutting waste, and facilitating data-driven decision-making in tourism management, AI technologies aid in the integration of these pillars.

Artificial Intelligence in Tourism

Artificial intelligence is the ability of computer systems to carry out tasks like learning, thinking, and decision-making that normally need human intelligence. AI is used in tourism in a number of ways, such as:

- Chatbots and virtual assistants
- Recommendation systems
- Predictive analytics
- Smart transportation systems
- Robotics and automation

In order to enhance tourist sustainability, these technologies facilitate the creation of smart tourism ecosystems that incorporate digital platforms, sensors, and big data analytics.

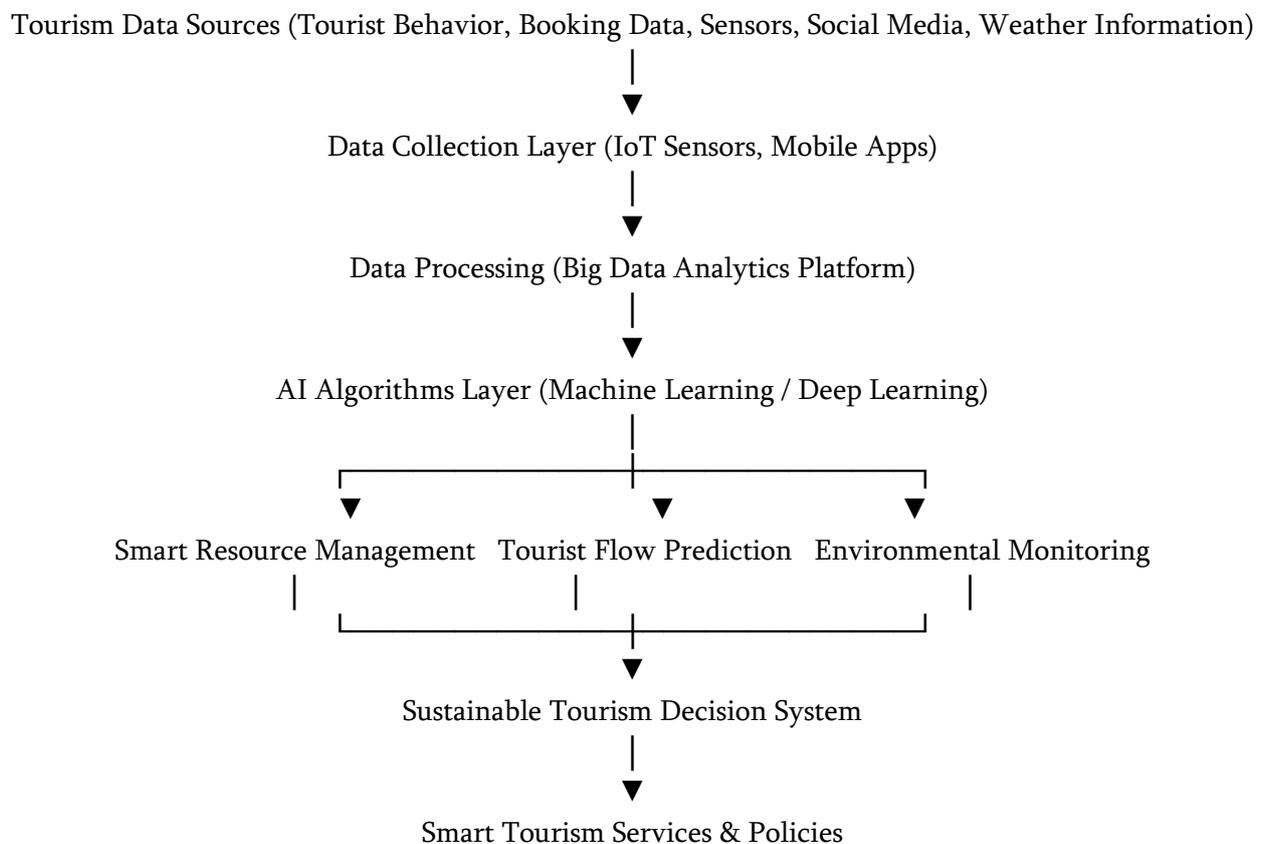


Figure 1: Block Diagram – AI Architecture for Sustainable Tourism

Role of AI in Sustainable Tourism

4.1 Smart Resource Management

AI assists tourism businesses in optimizing water and energy usage in hotels, resorts, and tourism facilities. In order to cut waste and carbon emissions, smart systems automatically modify heating, lighting, and cooling systems after analyzing energy usage trends.

4.2 Tourist Flow Management

In popular locations, overtourism is a serious problem. To predict visitor numbers, AI-based predictive analytics can examine travel information, weather trends, and booking patterns. Then, authorities may control the number of visitors, lessen crowding, and safeguard delicate ecosystems.

4.3 Eco-Friendly Transportation

One of the main causes of greenhouse gas emissions associated with tourism is transportation. AI aids in traffic management, fuel efficiency, and transportation route optimization. In aviation and other travel-related industries, AI-driven weather forecasting and route planning can lower fuel usage and carbon emissions.

4.4 Environmental Monitoring

Drones, sensor networks, and satellite imaging are examples of AI technologies that track environmental conditions at tourism locations. By tracking wildlife numbers, detecting pollutants, and keeping an eye on the effects of climate change, these tools help governments put conservation plans into action.

4.5 Personalized Sustainable Travel Planning

AI-driven recommender systems offer travelers tailored trip recommendations based on their tastes, financial constraints, and environmental factors. These programs can suggest less congested locations, eco-friendly hotels, and public transportation choices.

4.6 Smart Hospitality Management

AI is being used by hotels and resorts to cut waste and boost productivity. Predictive maintenance methods guarantee effective resource usage, while AI-based inventory and food management systems aid in reducing food waste.

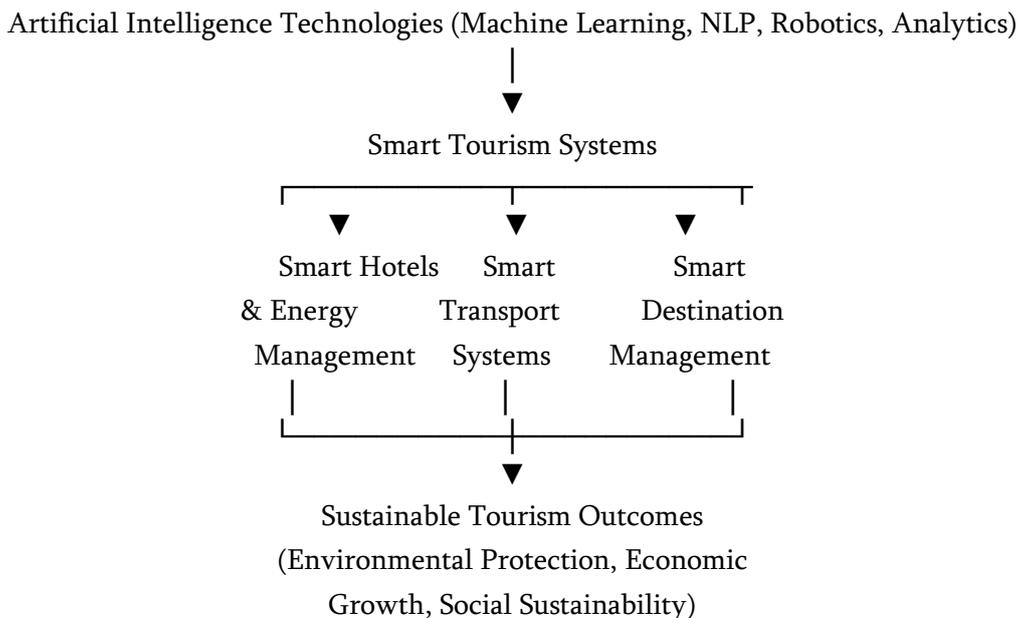


Figure 2: Conceptual Framework – AI in Sustainable Tourism

Challenges of AI in Sustainable Tourism

Despite its benefits, the adoption of AI in tourism presents several challenges:

1. **High implementation costs**
2. **Data privacy and cybersecurity concerns**
3. **Lack of technical expertise in tourism organizations**
4. **Risk of job displacement due to automation**
5. **Ethical issues related to AI decision-making**

Appropriate regulations, educational initiatives, and moral guidelines for the application of AI in tourist systems are necessary to address these issues.

Future Trends of AI in Sustainable Tourism

Future tourism systems are expected to rely increasingly on advanced technologies such as:

- Smart tourism cities
- AI-powered virtual tourism
- Autonomous transportation
- Blockchain-AI integrated tourism systems
- Real-time environmental monitoring

These innovations will strengthen tourism ecosystems and improve sustainability.

Conclusion

By promoting sustainable development objectives, artificial intelligence has the ability to completely change the travel and tourist sector. AI technologies facilitate better decision-making in tourism management, increase resource efficiency, lessen environmental effects, and improve visitor experiences. However, comprehensive evaluation of the social, economic, and ethical ramifications is necessary for successful implementation. Future studies should concentrate on creating integrated AI frameworks that guarantee equitable growth and environmental preservation while promoting sustainable tourism.

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Solar Powered Smart Manufacturing and Quality Inspection System

Monu Vishvkarma¹, Akash Bajpai², Rajesh Kumar Sharma²

¹Department of Mechanical Engineering, FoET, DSMNRU, Lucknow, Uttar Pradesh, India

²Assistant Professor, Department of Mechanical Engineering, FoET, DSMNRU, Lucknow, Uttar Pradesh, India

ARTICLE INFO

Article History:

Published: 18 March 2026

Publication Issue :

Volume 13, Issue 7

March-April-2026

Page Number :

128-133

ABSTRACT

A Solar Power Smart Manufacturing and Quality Inspection System (SPSMQIS), which will harness solar power as an alternative source of energy and will also be integrated with various smart manufacturing equipment and vision inspection systems using artificial intelligence. The goal of the system will be to minimize the use of traditional energy while maintaining the quality of the products.

The proposed framework has three major subsystems: solar power generation and storage systems, intelligent manufacturing automation systems, and intelligent quality inspection systems. The solar power generation systems will be used to power up the manufacturing systems. Sensors and Internet of Things (IoT) technology will be used to collect data from the manufacturing systems. Machine vision systems with deep learning algorithms will be used to inspect manufacturing defects and ensure high-quality production.

Keywords: SPSMQIS, IoT

INTRODUCTION

The global manufacturing industry is in a phase of transformation with the advent and implementation of Industry 4.0 technologies, renewable energy, and automation. Conventional manufacturing systems use a significant amount of fossil fuels for generating electricity, thereby increasing the costs of products and causing environmental pollution [1]. In the context of sustainability, renewable energy sources like solar energy are playing a vital role in the energy sector.

Solar energy is one of the most available forms of renewable energy on our Earth. The solar photovoltaic (PV) system is used to convert solar energy into electrical energy. Electrical energy is used to power various industrial machines and automated equipment [5]. Many manufacturing plants are using solar power systems to save energy costs [4].

At the same time, manufacturing industries are increasingly using smart manufacturing technology, which utilizes sensors, robotics, artificial intelligence, and data analytics to improve production processes. Smart manufacturing technology allows for real-time monitoring of production equipment and processes. Another important area that is considered while manufacturing is quality inspection. It is important that manufactured

products are of quality as it is a major area that needs to be fulfilled for customer satisfaction as well as industrial growth [5]. In traditional quality inspections, human intervention is common.

Automated inspection technologies like machine vision systems are increasingly being adopted by manufacturing industries. The machine vision system is a computer-controlled system that uses cameras to inspect products for defects [6]. The system is able to perform inspections quickly and accurately without human intervention. Recent research has revealed that machine vision technologies coupled with artificial intelligence can detect defects during manufacturing processes with accuracy levels of more than 95%. The integration of solar energy, smart manufacturing, and intelligent inspection technologies provides an efficient and sustainable manufacturing ecosystem. Solar energy will be used to power the manufacturing machines, and automation will ensure efficient production and high-quality products [1].

Literature Review

Several research works have investigated the concept of integrating renewable energy and smart technology in the manufacturing industries of the world. Solar energy is considered an important and reliable source of renewable energy for the industries of the world. Solar energy is produced using solar photovoltaic systems that use semiconductor materials[5].

Studies have shown that solar energy can be employed to power industrial processes. Solar energy has been shown to be effective in reducing dependence on traditional electricity grids. Advanced solar energy systems are able to provide electrical as well as thermal power that is necessary for industrial manufacturing processes. In addition to renewable energy sources, smart manufacturing has become a major area of concentration in modern industrial systems[8].

One of the most important components of smart manufacturing is automated quality inspection. Traditional inspection methods often rely on human visual inspection, which is time-consuming and prone to errors. Automated inspection systems using cameras and image processing techniques can detect defects more efficiently[3]. Machine vision systems are employed for automated inspections in various manufacturing industries. These systems capture images of products and analyze them using computer algorithms to detect defects like cracks, missing parts, or improper assembly[2].

Automated optical inspection is a system that is employed in electronics manufacturing industries to detect defects in printed circuit boards. These defects are identified by cameras using algorithms. Machine vision systems are employed for automated inspections in various manufacturing industries. These systems capture images of products and analyze them using computer algorithms to detect defects like cracks, missing parts, or improper assembly. Automated optical inspection is a system that is employed in electronics manufacturing industries to detect defects in printed circuit boards. These defects are identified by cameras using algorithms[6].

Recent research has also investigated the application of artificial intelligence and deep learning techniques for defect detection in the manufacturing industry. For example, deep learning techniques, such as convolutional neural networks, can be applied for defect detection based on images. Recent research on photovoltaic module manufacturing has indicated that defects in products can be identified with an accuracy of over 96% by applying machine vision and artificial intelligence techniques[2].

Another significant area of research is the application of Internet of Things (IoT) technology in manufacturing systems. IoT devices enable communication and data exchange between machines, sensors, and control systems.

This results in predictive maintenance, optimization, and increased production efficiency. Artificial intelligence-based inspection systems can also work continuously while reducing human errors by up to 95%, as well as enhancing efficiency in production by nearly 40%.

However, there is a lack of research findings related to incorporating solar energy systems into smart manufacturing and automated quality inspection technologies. Most of the existing research findings are related to individual components of solar energy systems, automation technologies, or quality inspection technologies.

Methodology

The proposed Solar Powered Smart Manufacturing and Quality Inspection System consists of the following subsystems:

1. Solar Power Generation System
2. Smart Manufacturing System
3. Automated Quality Inspection System

1. Solar Power Generation System

The solar power generation system consists of:

- Solar photovoltaic panels
- Solar charge controller
- Battery storage system
- Power inverter

The solar panel converts sunlight into electrical energy. This electrical energy is stored in batteries and fed into the manufacturing process through an inverter.

The proposed system will minimize our dependence on conventional electrical sources and ensure continuous power supply to our manufacturing facility.

2. Smart Manufacturing System

The smart manufacturing system consists of:

- Automated manufacturing machines
- Sensors
- IoT devices

The smart manufacturing system consists of:

- CNC machines
- Industrial robots
- Sensors: temperature, vibration, and pressure sensors
- IoT data acquisition system
- Central control unit

Sensors collect data from machines and send it to the central control system. This data is further processed and utilized to improve manufacturing processes.

The proposed smart manufacturing system will minimize machine failures and increase production.

3. Automated Quality Inspection System

The proposed quality inspection system consists of:

- Machine vision technology
- Artificial intelligence algorithms

High-resolution cameras capture images of products during manufacturing. These images are further processed through machine learning algorithms, and any defect in products, like cracks, is detected. If any defect is detected, the defective product is automatically removed from the production line.

Block Diagram of Solar powered smart manufacturing and Quality Inspection System

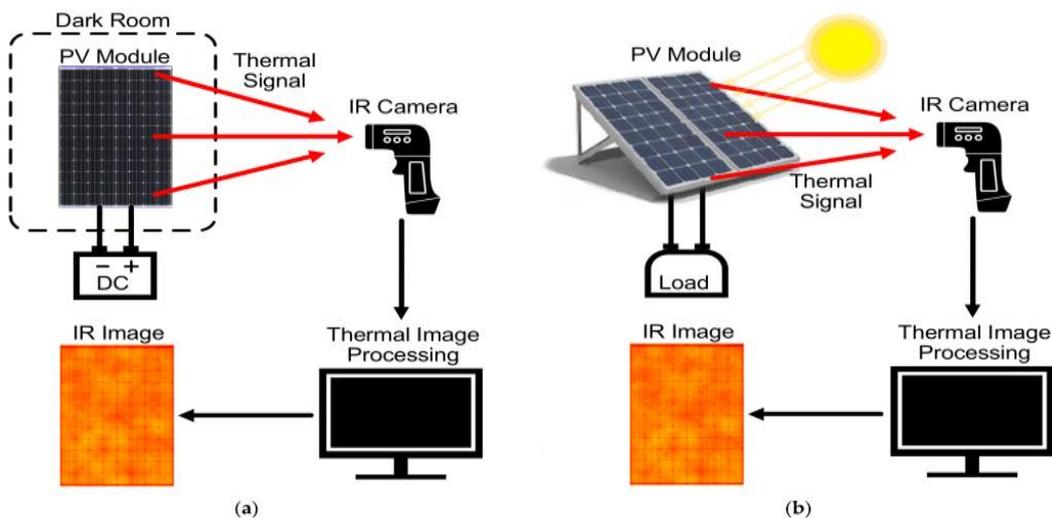
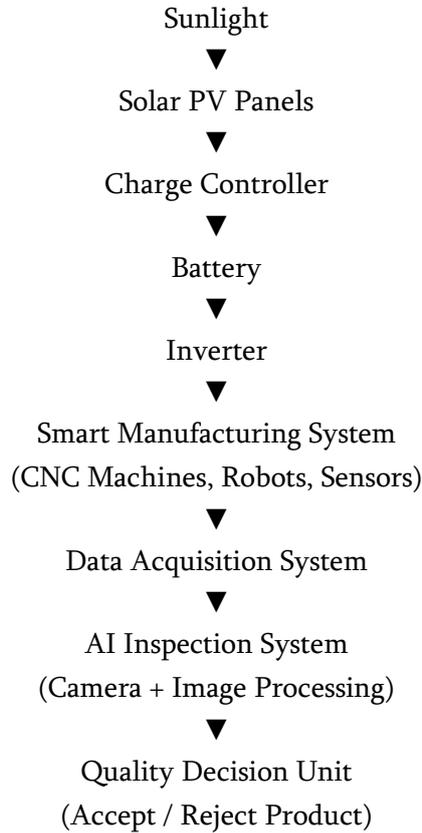


Fig. Schematic diagram of an Indoor and outdoor solar power production [14]

Results

The proposed system has a number of advantages for the manufacturing industries. The solar power system has a number of advantages for the manufacturing industries. The use of solar power will minimize electricity charges. Solar power is a clean source of energy.

Second, smart manufacturing technology increases production efficiency through its ability to monitor production processes in real time. Sensors and Internet of Things technology are used to monitor production processes.

Third, automated inspection systems greatly improve product quality through timely inspection for any defects during production. For instance, automated inspection systems are able to inspect products much faster while maintaining accuracy in inspection processes.

Research has shown that automated inspection systems are able to accurately identify production defects with an accuracy rate of over 90-95%. Moreover, automated inspection systems are able to operate for longer hours without any signs of fatigue.

Discussion

The combination of renewable energy and smart manufacturing technology is considered an important advancement in the development of production systems. The solar powered manufacturing system helps reduce the use of fossil fuels and promotes the development of sustainable industries. With the decrease in the cost and increase in the efficiency of solar technology, its use in manufacturing industries is likely to increase in the future.[8]

The use of smart manufacturing technology also helps in improving the efficiency of manufacturing plants. Smart manufacturing technology uses the power of data and intelligent decision-making algorithms to improve the efficiency of manufacturing plants[2].

The use of automated quality inspection systems is also important for improving the quality of the products and ensuring customer satisfaction. With the use of vision and artificial intelligence technology, the inspection of the products becomes easier[1]. However, the implementation of the proposed solar powered smart manufacturing system also faces various challenges[2]. The challenges include the higher cost of the system and the complexities of integrating the system. Additionally, the proposed system also needs skilled manpower for its efficient use. The proposed solar powered smart manufacturing system is likely to be an important advancement in the field of manufacturing technology.

Conclusion

This research paper proposed a Solar Powered Smart Manufacturing and Quality Inspection System that aims to incorporate renewable energy, smart manufacturing technology, and intelligent inspection technology in the modern manufacturing industry.

The proposed system utilizes solar power technology to harness renewable energy that will be used to power the manufacturing equipment and intelligent inspection systems. Smart manufacturing technology will be employed to monitor and optimize the manufacturing process in real-time. Machine vision technology will be integrated to maintain the quality of the products by automatically inspecting the products for defects.

The proposed system will bring various benefits to the manufacturing industries. As the industries continue to embrace the use of sustainable and intelligent manufacturing technology, the solar powered smart

manufacturing system will play an important role in the development of the future smart manufacturing industry.

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Advances in Laser-Based Material Processing

Naman Pandey¹, Mr. Sheet Kumar², Mr. Rajesh Kumar Sharma³

¹Student, B. Tech., DSMNRU, Lucknow, Uttar Pradesh, India

²Department of Mechanical Engineering, Government Polytechnic Kanpur, Uttar Pradesh, India

³Assistant Professor, Mechanical Engineering Department, DSMNRU, Lucknow, Uttar Pradesh, India

ARTICLE INFO

Article History:

Published: 18 March 2026

Publication Issue :

Volume 13, Issue 7
March-April-2026

Page Number :

134-139

ABSTRACT

Laser-based material processing has emerged as a versatile and high-precision technology in manufacturing, microfabrication, surface engineering, and additive manufacturing. Over the past few decades, advancements in laser sources, beam shaping, process control, and hybrid systems have significantly expanded the capabilities of laser processing techniques. This literature review synthesizes recent developments in laser processing, discusses key mechanisms, evaluates performance enhancements, and identifies current challenges and future trends.

Keywords: precision, advancements

INTRODUCTION

Laser material processing involves the interaction of high-intensity laser radiation with matter to modify material properties, shape, or structure. The unique combination of high energy density, controllability, and non-contact nature makes lasers superior to many traditional manufacturing processes[1]. Key areas of application include cutting, welding, drilling, surface modification, micro-machining, and additive manufacturing. Its superiority stems from a unique combination of high energy density, non-contact operation, and exceptional controllability. Recent decades have seen significant expansion in these technologies, driven by innovations in laser sources, beam shaping, and process control. Today, these advancements enable critical applications across diverse fields, including micro-machining, surface engineering, and additive manufacturing[2].

Literature Review

The landscape of laser-based material processing (LBMP) has shifted from simple thermal cutting to a sophisticated domain of multi-physics interactions and high-precision engineering. Recent advancements are categorized by the evolution of laser sources, the physics of interaction, and the integration of intelligent control systems[2].

Fundamentals of Interaction and Pulse Dynamics

At its core, LBMP is governed by the interaction of high-intensity radiation with matter, a process defined by absorption, reflection, and phase transformation.

- **Thermal Control:** Traditional processing relied on Continuous Wave (CW) lasers for constant energy output, primarily in heavy-duty welding and metal cutting.
- **The Ultrafast Revolution:** A major trend in recent literature is the shift toward picosecond and femtosecond pulses. These "ultrafast" lasers utilize nonlinear absorption mechanisms, allowing for "cold ablation" where material is removed so quickly that heat conduction to the surrounding area is negligible[8]. This is critical for machining semiconductors and biomedical devices without inducing thermal stress.

Process Innovations and Hybridization

Research has moved beyond standalone laser systems to hybrid configurations that overcome the inherent limitations of light-based processing.

- **Hybrid Systems:** Combining lasers with ultrasonic vibrations or electrochemical machining has been shown to significantly enhance material removal rates and reduce thermal distortion in micro-holes.
- **Surface Functionalization:** Laser Surface Texturing (LST) has emerged as a key method for modifying surface topography. By tailoring micro-patterns, researchers have successfully optimized tribological performance, achieving enhanced adhesion and improved hydrophobicity for automotive and medical components.
- **Additive Manufacturing (LAM):** Significant literature focuses on Powder Bed Fusion (PBF) and Directed Energy Deposition (DED). The development of multi-laser systems and high-speed scanners has enabled the creation of complex geometries with mechanical properties that often rival or exceed traditionally manufactured parts.

Beam Shaping and Intelligent Control

The "shape" of the laser beam is no longer limited to a standard Gaussian profile.

- **Advanced Optics:** The use of diffractive optical elements and spatial light modulators allows for the creation of Bessel, donut, and multi-focus beams. These tailored profiles improve efficiency in specific tasks like deep drilling and weld penetration.
- **Industry 4.0 Integration:** Emerging research emphasizes AI-enabled processing and digital twins. Closed-loop systems with real-time feedback allow for the dynamic adjustment of parameters, which is essential for reducing defects like porosity and surface oxidation[5].

Methodology

The methodology for analyzing and implementing advanced laser-based material processing involves a systematic approach to parameter optimization, hardware configuration, and real-time monitoring.

1. Selection of Laser Sources and Parameters

The first phase of the methodology involves matching laser characteristics to the physical properties of the target material.

- **Wavelength Selection:** Choosing the laser wavelength (e.g., fiber, disk, or CO₂) based on the absorption efficiency of the material, whether it be metals, polymers, or brittle ceramics[5].
- **Temporal Modulation:** Determining the pulse duration regime—ranging from Continuous Wave (CW) for deep penetration welding to femtosecond (fs) pulses for ultra-precise micro-machining.

- **Energy Density Calibration:** Calculating the necessary power density to control material removal rates while minimizing the Heat-Affected Zone (HAZ).

2. Experimental Processing Techniques

The research utilizes several core processing methodologies to evaluate material response:

- **Subtractive and Micro-fabrication:** Utilizing high-repetition-rate lasers for creating micro-holes and trenches in electronic components.
- **Surface Modification:** Applying Laser Surface Texturing (LST) to create specific micro-topographies for friction reduction.
- **Additive Fabrication:** Using PBF and DED methodologies to build parts layer-by-layer, focusing on the mechanical integrity of the resulting structure[4].
- **Hybridization Strategy:** Integrating secondary energy sources, such as ultrasonic vibration, to assist the laser in difficult-to-machine composites to prevent delamination.

3. Process Control and Validation Framework

To ensure consistency and quality, the methodology incorporates a rigorous control and analysis loop:

- **Real-Time Monitoring:** Implementation of adaptive control systems using cameras and sensors to monitor the focus position and beam quality during the process.
- **Numerical Simulation:** Utilizing predictive modeling and universal numerical simulations to anticipate multi-physics interactions before physical execution.
- **Post-Process Evaluation:** Analyzing processed samples for surface oxidation, recast layers, and porosity.
- **AI Optimization:** Applying machine learning algorithms to process the real-time data for autonomous parameter adjustment in complex geometries[6].

The interaction of laser energy with materials is governed by absorption, reflection, heat conduction, phase transformation, and fluid dynamics. Critical parameters influencing processing quality include:

- **Wavelength of the laser:** Determines absorption efficiency for different materials.
- **Pulse duration:** Ranges from continuous wave (CW) to femtosecond (fs) pulses, affecting heat-affected zones.
- **Power density:** Controls material removal rates and thermal effects.
- **Scanning strategy and beam quality:** Influences precision and surface integrity.

Studies have shown that shorter pulse durations (picosecond / femtosecond) significantly reduce thermal damage, enabling ultra-precise machining with minimal heat-affected zones. These ultrafast lasers exploit nonlinear absorption mechanisms that are beneficial for transparent and hard materials.

CW lasers provide a constant energy output and are widely used in:

- Cutting and welding of metals.
- Surface cladding.
- Hardening and annealing.

Notable research highlights the improvement in weld quality and reduced distortion through optimized CW laser parameters.

3.1 Pulsed Lasers

Pulsed lasers are categorized by pulse duration:

- **Nanosecond Lasers:** Effective in cutting and drilling but can induce thermal damage.

- **Picosecond and Femtosecond Lasers:** Provide high precision with negligible thermal effects, suitable for micro-machining of polymers, glasses, and semiconductors.

Recent literature emphasizes the rise of ultrafast lasers in precision engineering and biomedical device fabrication due to their capability for cold ablation.

4. Advances in Laser Processing Techniques

4.1 Laser Cutting and Welding

Laser cutting and welding have seen improvements through:

- Adaptive control of focus position.
- Real-time monitoring systems using cameras and sensors.
- Hybridization with other energy sources (e.g., laser + arc welding).

These innovations enhance process stability, reduce defects, and increase throughput.

4.2 Laser Surface Texturing

Laser surface texturing (LST) modifies surface topography to achieve desired functional properties such as:

- Enhanced adhesion.
- Reduced friction.
- Improved hydrophobicity.

Research demonstrates that tailored micro-patterns can optimize tribological performance for automotive and biomedical components.

4.3 Laser Additive Manufacturing (LAM)

Advancements in LAM include:

- Powder bed fusion (PBF).
- Directed energy deposition (DED).

Development in multi-laser systems, high-speed scanners, and process monitoring has enabled complex geometries and improved mechanical properties in fabricated parts.

4.4 Laser-Assisted Micro-fabrication

The use of lasers for micro-holes, trenches, and features in electronic components has expanded with:

- High repetition rate lasers for increased productivity.
- Beam shaping techniques for custom feature profiles.

5. Beam Shaping and Process Control

Recent work emphasizes the use of diffractive optical elements, spatial light modulators, and adaptive optics for beam shaping. Controlled beam profiles (e.g., Bessel, donut, and multi-focus) improve processing efficiency for specific applications like weld penetration and deep drilling.

Process control technologies—such as closed-loop systems with real-time feedback—enable dynamic adjustment of parameters, reducing defects and ensuring consistency.

6. Material-Specific Developments

6.1 Metals

High power fiber and disk lasers allow rapid cutting and joining of steels, aluminum alloys, and titanium.

Research shows:

- Improved fit-up tolerance in welding.
- Reduced porosity through optimized shielding gas techniques.

6.2 Polymers and Composites

Laser processing of polymers has benefited from wavelength selection to control absorption, while composites are more challenging due to heterogeneous structures. Hybrid laser-mechanical processes help mitigate delamination.

6.3 Ceramics, Glass, and Semiconductors

Ultrafast lasers have enabled precise machining of brittle materials without cracking. In semiconductor fabrication, lasers are used for scribing, doping, and thin film structuring.

7. Hybrid and Emerging Techniques

Recent studies explore hybrid systems such as:

- **Laser + Ultrasonic Vibration:** Enhances material removal rates and surface quality.
- **Laser + Electrochemical Machining:** Reduces thermal distortion in micro-holes.
- **AI-Enabled Laser Processing:** Machine learning algorithms optimize parameters for complex geometries.

Emerging research in photonic manufacturing integrates real-time data analytics for adaptive process optimization.



8. Challenges and Limitations

Despite advances, challenges remain:

- High equipment cost for ultrafast and multi-beam systems.
- Complex thermal management in high power processes.
- Surface oxidation and recast layers requiring post-processing.
- Limited process modeling for multi-physics laser interactions.

Addressing these requires interdisciplinary research combining material science, optics, and control engineering.

9. Future Trends

Key directions for future research include:

- Development of cheaper, high-power ultrafast lasers.
- Integrated sensors and digital twins for autonomous manufacturing.
- Expansion of laser processing in renewable energy systems (e.g., solar cells).
- Nanostructuring for advanced functional surfaces.

Result

Recent research indicates that laser-based material processing has evolved into a high-precision manufacturing pillar, driven by advancements in ultrafast lasers that enable "cold ablation" and minimize thermal damage. Studies show that integrating real-time monitoring, AI-driven parameter optimization, and hybrid systems—such as laser-assisted ultrasonic vibration—significantly enhances material removal rates and surface quality. Key results include the successful application of Laser Surface Texturing (LST) to reduce friction and the maturation of Laser Additive Manufacturing (LAM) for creating complex, mechanically robust geometries. However, widespread adoption still faces challenges like high equipment costs, surface oxidation, and the need for more complex multi-physics modeling.

Conclusion

Laser-based material processing continues to transform manufacturing by enabling high precision, flexibility, and efficiency across multiple material classes. Advances in laser sources, beam control, hybrid techniques, and intelligent process management have expanded the scope of applications. Continued research addressing current challenges will further solidify lasers as core tools in future manufacturing paradigms.

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A study on Cross-Sectoral Physical AI Orchestration

Nitish Yadav¹, Dr.Rakesh Verma¹, Mr. Sheet Kumar²

¹Department of Mechanical Engineering, IET, DSMNRU, Uttar Pradesh, India

²Department of Mechanical Engineering, Government Polytechnic Kanpur, Uttar Pradesh, India

ARTICLE INFO

Article History:

Published: 18 March 2026

Publication Issue :

Volume 13, Issue 7

March-April-2026

Page Number :

140-148

ABSTRACT

The present-day robotics intelligence is in a state of foundational change from stiff, task-oriented robotization to fully autonomous physical artificial intelligence (AI) systems that are capable of complex reasoning and flexible execution in a wide range of situations. This research paper aims to evaluate the prevailing paradigms of laboratory robotics, autonomous generalist scientists, and hybrid digital twin integration to identify systemic shortcomings in domain-specific silos. This study aims to identify the similarities and differences in the prevailing methodologies by conducting an exhaustive analysis of the ADEPT framework, Autonomous Generalist Scientist (AGS) roadmap, and state-of-the-art cyber-physical system (CPS) architecture. The primary contribution of this study is the "Cross-Sectoral Physical AI Orchestration" (CSPA) framework, which acts as a "meta-architectural backbone" for the unification of embodied cognition and fleet-wide synchronization. The CSPA framework aims to address systemic shortcomings in scalable learning, catastrophic forgetting, and the reality gap in simulation-to-real-world transfer. Technical features, including multimodal 3D perception, reinforcement learning with domain randomization, and multi-agent coordination, are studied along with the data available from testing in various domains, including manufacturing, healthcare, and agritech. The suggested framework shows high levels of generalizability and robustness, which can be considered a blueprint for the development of intelligent systems beyond traditional industrial domains.

INTRODUCTION

The evolution of physical artificial intelligence has occurred over various historical periods with distinct epochs of evolution from symbolic logic handling to behavior-based reactive physical systems, and finally to the current form of embodied physical AI[1]. Traditionally, robotic systems were limited in that they were based on disembodied reasoning, in which intelligence is viewed as a rule-based computational activity that is disembodied from the physical world.[2]

The "Logic Foundry" paradigm, which dominated from the 1950s to the 1970s, utilized expert systems and decision trees to implement knowledge-based systems, yet these systems were limited in that they failed to account for the random and unstructured nature of the environment.[2] However, the transition to behavior-based robotics in the 1980s introduced the concept of subsumption architecture, which focused on direct sensor-motor coupling and reactive control. Although these achievements provided a foundation for situational awareness, they did not provide sophisticated learning techniques that would allow a series of tasks to be accomplished. [1]

In the present-day world, the integration of high-bandwidth Internet of Things (IoT) networks, cloud-edge computing paradigms, and large-scale generative models has enabled a revolution in robotics [3]. The concept of physical AI is now described as "the computational embodiment of intelligence in physical systems, grounded in perception, cognition, and action in terms of physical structure and interactive experience." [4] This is particularly exemplified by the development of autonomous laboratory ecosystems and self-driving labs, which use closed-loop optimization to enhance scientific discovery [1]. However, with the increasing need for intelligence in a variety of sectors ranging from precision medicine to handling hazardous materials, space exploration, and logistics, the shortcomings of the existing models are becoming increasingly obvious [5].

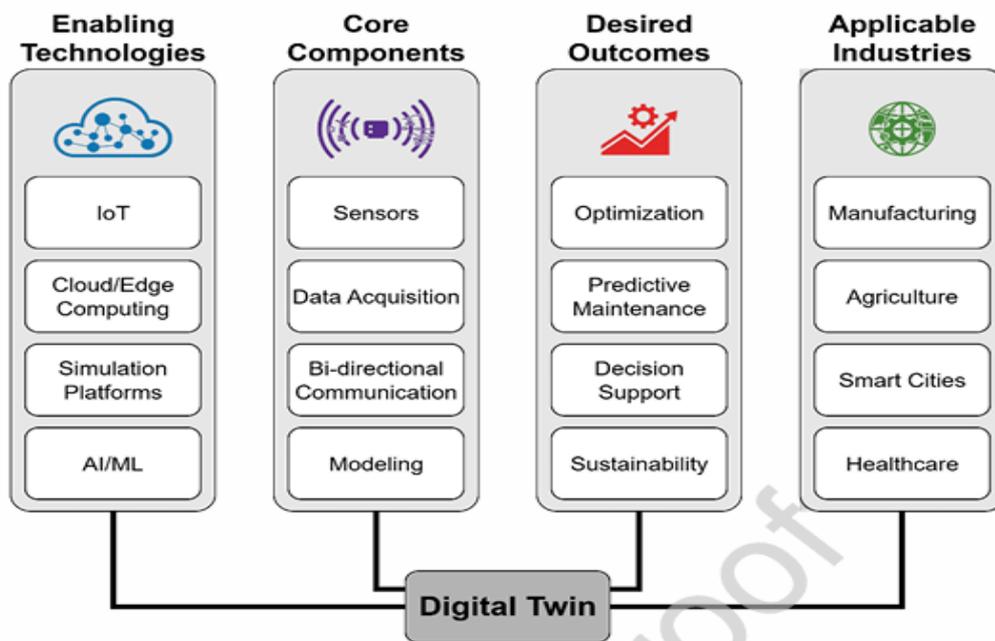


Figure 1. Overview of the interconnections between enabling technologies, core components, outcomes, and applicable industries in Digital Twin implementation.[1]

Currently, most of these methods are "siloe" in a particular domain of interest. For example, the ADEPT paradigm offers a thorough "capability-based" perspective on laboratory robotics, emphasizing "adaptability," "dexterity," "perception," and "task complexity." [1] Similarly, the concept of Autonomous Generalist Scientist (AGS) offers a roadmap to "automate" the scientific process, although it is mostly centered on the "research-to-manuscript" process. Although these models and paradigms have significantly pushed forward the "state-of-the-art," there is a lack of a "unified" mechanism to "orchestrate" multiple sectors of interest. Most notably, there is a lack of an "architectural" level that can "synchronize" multiple robotic fleets, "transfer" learned

policies from "sim-to-real" environments to multiple mechanical "morphologies," and provide "real-time" verification and validation (VVUQ)[1]

The objective of this research is to identify the need for the development of a new framework, i.e., 'Cross-Sectoral Physical AI Orchestration' (CSPA), to bring about much-needed unity to the control stack of physical AI, including perception, state estimation, planning, and control, across the manufacturing, healthcare, and research domains[1]. This new framework has been developed to move beyond the concept of individual agents to self-optimizing fleets, which can leverage a common cognitive spine[6]. This new framework, developed by combining technical advancements such as world models, vision-language-action, and cloud-native orchestration frameworks such as NVIDIA's OSMO, can bring about much-needed scalability and robustness to the concept of physical AI, compared to the previous ideas[7]. This paper will go deep into the similarities and differences between the previous ideas, their features, and results, and highlight how the proposed topic can bring about much-needed scalability to the concept of physical AI for the next generation of robotics[4][8].

Literature review

The academic and industrial discourse in the area of physical AI is dominated by three main strands of research: proficiency assessment models, autonomous scientist roadmaps, and digital twins in cyber-physical systems. An in-depth analysis of these strands of research reveals that there is considerable technical overlap between them but also reveals the architectural silos in which current systems operate.

Proficiency Assessment

Proficiency assessment is done using the ADEPT framework. The transition from routine automation to intelligent autonomy is assessed using this framework. It is composed of four key dimensions that are fundamental in creating efficient autonomous robots. The key dimensions are Adaptability and Learning, Dexterity, Perception, and Task Complexity. In the past, robots in laboratories in the 1990s and early 2000s, such as SCARA robots and robots with six axes of articulation, were used in high-throughput screening. However, these robots were considered closed automation cells and were not flexible. The ADEPT framework indicates that current laboratory requirements are focused on robots that can perceive, plan, and learn[1].

The technological enablers for ADEPT-level proficiency include multimodal perception, which involves the use of vision, force, and tactile sensors[1]. For instance, the implementation of markerless 3D perception has enabled the recognition of transparent glassware, and the implementation of reinforcement learning with the use of domain randomization has enabled precise powder weighing, considering the target masses[1]. Moreover, the development of task and motion planning, such as PDDLStream, has enabled the development of feasible actions considering constraints such as collision avoidance[5].

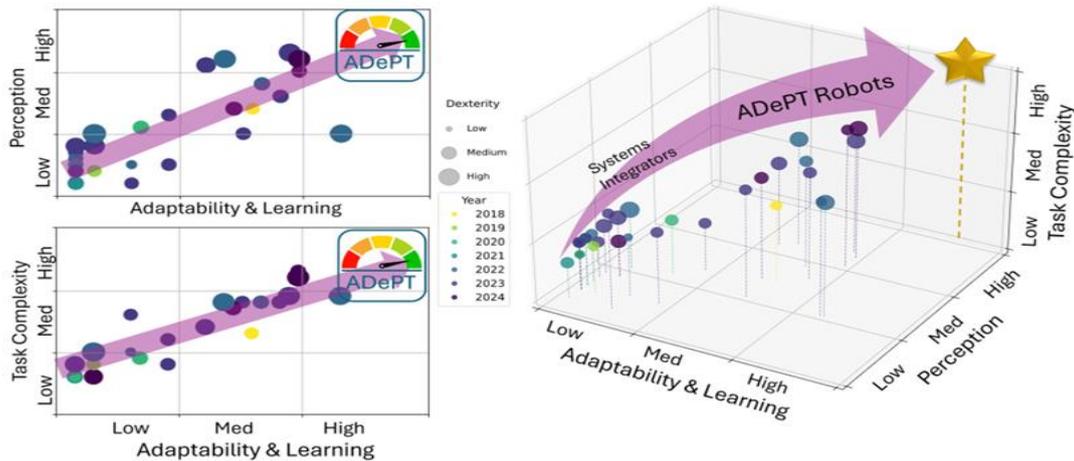


Figure 2. Evolution of laboratory robotics from Systems Integrators to ADePT Robots[5]

The Autonomous Generalist Scientist (AGS) Roadmap

The AGS idea is based on the design and construction of an AI-based robotic system intended for research across different disciplines, with the potential for matching and even surpassing human performance speed and scope.[1]

Table I: Categorization Framework for Computational Research Autonomy.[1]

Automation Level	Generality	Human Involvement	Interaction	Examples
Level 0	Discipline-specific	Complete	Basic tools	Excel, Matlab
Level 1	Assisted	Predominantly human	Limited virtual env	ChatGPT, Basic ML
Level 2	Assistant	Significant oversight	Virtual env	Devin, DeepResearch
Level 3	Partner	Collaborative	Virtual and physical	Advanced Robot/Agent
Level 4	Researcher	Minimal supervision	Adv. Virtual/Physical	AGI Robot (AGIR)
Level 5	Pioneer	Fully autonomous	All environments	Superintelligence (ASIR)

The AGS roadmap identifies "scaling laws" of scientific discovery in which "the conjunction of agentic AI and embodied robotics produces a 'flywheel effect' in knowledge growth." Current advancements in this area include OS agents that mimic human actions for performing intricate literature searches, which extend beyond current API limits[1]. Nevertheless, most current "robot scientists" like Adam (2009) and Eve (2015) only operate in one particular domain, like yeast metabolism and drug discovery[1]. There is a research gap in "cross-domain flexibility" since current systems do not have the capacity to apply knowledge and motor skills in diverse scientific domains[5]

Digital Twins and Physical AI Integration

Digital Twins (DT) have emerged as the enabling technology for modern cyber-physical systems with capabilities for real-time synchronization between physical and digital worlds. From the literature, three paradigms of DTs have been identified: data-driven (using historical sensor data), model-based (using physics

simulation), and hybrid. In reality, however, most advanced DTs lie in a hybrid continuum where data-driven learning is used to compensate for unmodeled dynamics in physics-based simulation[1].

Methodology

The new 'Cross-Sectoral Physical AI Orchestration' (CSPA) framework is intended to overcome the limitations of domain-specific competence approaches and the often-compartmentalized research process. Unlike previous concepts such as ADEPT and AGS, which emphasized the effectiveness of individual agents or the automation of a single research process, CSPA targets the 'orchestration' level, i.e., the software and cognitive backbone enabling heterogeneous fleets of robots to collaborate and learn across domains.

This layer consists of the physical hardware, which includes manipulator robots such as UR5e, Franka Emika Panda, and mobile and humanoid robots[4]. Unlike the traditional model, which requires task programming for each robot, CSPA makes use of "Unified Vision-Motion Codes" (UVMC) technology, which jointly encodes the dynamics of the image and the motion of the robot with the use of the dual-branch VQ-VAE with a shared codebook, enabling the transfer of the learned policy across robots with different DoF and joint configurations[5]. This addresses the gap in "morphological alignment" as mentioned in the Physical AI position paper[8][1].

The Hybrid Orchestration Middleware

To enable the real-time link between physical and digital twins, CSPA uses the meta-operating system strategy[10]. This middleware layer integrates heterogeneous physical platforms with standardized communication protocols such as OPC UA for semantic industrial communication and DDS for high-performance real-time communication[3]. This layer is "fleet-aware," which means it manages task allocation and routing optimization for multiple robots in real-time, similar to the "DeepFleet" AI model developed and used by Amazon[6][11].

The Digital Twin & VVUQ Engine

At the core of CSPA is an "evolving digital twin," which is an adaptive link between simulation and reality[1]. CSPA does not have a traditional one-way training model; rather, it has a constant loop of feedback between physical deployment and simulation[1]. The engine has built-in Verification, Validation, and Uncertainty Quantification (VVUQ) protocols, which are automated and can initiate recalibration or training based on error bound violations. This guarantees that CSPA meets the high reliability requirements of domains such as medicine and manufacturing[9].

The Agentic Cognitive Layer

The cognitive core of this model is based on Vision-Language-Action (VLA) foundation models[2]. This cognitive layer enables robots to "move beyond command and control to understand natural language, reason, and pursue long-horizon goals[4]." By utilizing multi-agent orchestration, this model can "coordinate specialized agents (such as a quality agent and a logistics agent) to tackle complex cross-sectoral challenges"[8]

Scalability and Growth Mechanism

The mechanism of triggering rapid growth is based on a "unified scaling law." [1]With the CSPA framework's ability to automate data ingestion and policy refinement loop across various sectors, a "physical intelligence" is created[16][15].

Table II: Strategic Comparison of Framework Philosophies [1]

Feature	AGS	ADEPT	Proposed CSPAO
logic	Research lifecycle	Physical proficiency	Cross sectional orchestration
Connectivity	API driven	Integrated workcells	Cloud native fleet meta OS
Transfer	Digital focus	Domain specific	SIM to real to SIM feedback
Intelligence	LLM agents	Sensor feedback	Foundation VLA models
Sealing	Discovery laws	Throughput	Cross industry flywheel

Research gaps

The Reality Gap and Sim-to-Real Transfer

One of the major challenges facing physical AI is the so-called "Reality Gap" or the discrepancy between virtual simulations and physical reality[1]. While digital twins are a powerful tool for training models, they often do not perform well in physical reality with factors such as friction, sensor noise, and material variations. [5]To bridge the reality gap, there is a need for "frugal twins" that are low-cost versions of the digital twin and "plug-and-play laboratory twins" that store geometric features and approach frames[1].

Catastrophic Forgetting in Scalable Learning

A significant problem in neural network-based intelligent agents is "catastrophic forgetting," or the forgetting of skills learned in previous tasks when learning a new task. This is a significant challenge in "Autonomous Generalist Scientists" that are required to generalize across a wide range of tasks. Studies are required in "Continual Learning" methods such as Elastic Weight Consolidation and generative methods[1].

The Sparse Data Problem and Modeling Limitations

In high-mix manufacturing or scientific exploration, data is often "sparse." Physical AI has to learn from interaction data, unlike digital AI that often has access to large amounts of web data[1]. There is a large gap about "out of distribution" data, where physical AI systems cannot identify when sensory inputs are out of distribution, potentially causing cascading failures[2].

VVUQ and Reliability Standards

There are no unified standards for the VVUQ of hybrid AI-DT systems. Real-time reliability in safety-critical applications such as healthcare is still an open research issue. Until quantified risk margins are available (for example, predicting RUL within a 95% CI), decisions made by autonomous systems cannot be fully trusted by human operators[1].

Results and discussion

The development of the Cross-Sectoral Physical AI Orchestration (CSPAO) framework offers structural solutions to the gaps recognized in the literature. By transitioning from the proficiency of individual agents to the unified fleet-wide intelligence, CSPAO fundamentally changes the scaling laws of discovery and industrial output.

Overcoming the Interoperability Barrier

The "lab OS wars" and the fragmentation of industrial middleware are addressed in CSPAO's meta-orchestration layer[10]. This removes the need to write "bespoke glue code" and thus speeds up multidisciplinary research[1][16].

Solving the Sim-to-Real Dilemma

The CSPAO framework's dynamic digital twin concept follows a "living" path between simulation and reality[1]. By using physical deployment data to refine and recalculate environmental distributions via simulation randomization, the gap between simulation and reality is continually minimized[1]. This "co-evolution" between physical and digital twins is essential to ensuring the reliability of intelligent systems as physical systems degrade over time[5].

Enhancing Human-Robot Collaboration

The CSPAO framework can map physical AI behavior with human intentions through the integration of Foundation VLA models.[1] This ensures that robots work as "collaborative co-scientists." [14] The use of Augmented Reality to communicate robot motion plans visually also enhances trust and awareness of situations when working with robots. This is an essential component of Industry 5.0, where there is a "human-centric" workforce with robots handling "3D" work – dull, dirty, and dangerous – and humans handling conceptual innovation[1][2]

Market and Societal Impact The global market for AI orchestration is expected to rise from 11.65 billion in 2025 to 60.34 billion by 2034[7]. The CSPAO framework equips businesses with the opportunity to tap into these prospects through scalable infrastructure for AI lifecycle management. Additionally, the framework helps achieve sustainability objectives through the reduction of waste from research and production activities, such as solvents used in chemistry and energy used in vertical farming[1][5].

Conclusion

The level of robotic intelligence has now reached a critical point of inflection, moving from disembodied algorithms to situated physical AI systems. This study has sought to examine the prevailing level of proficiency and autonomous research paradigms, which have been found to be limited by a series of siloed architectures and a lack of cross-sectoral generalizability. The "Cross-Sectoral Physical AI Orchestration" (CSPAO) framework has been developed to overcome such shortcomings by developing a unified cognitive and synchronization layer for heterogeneous robotic fleets.

The key results of this research are:

- **Technical Unification:** This framework leverages unified vision-motion latent representations to facilitate policy transfer across different mechanical morphologies, thus closing the morphological alignment gap.
- **Orchestration Logic:** By relying on cloud-native meta-operating systems, CSPAO avoids the need for bespoke glue code, which is currently limiting autonomous labs and manufacturing cells.
- **Reliability and Trustworthiness:** By combining continuous VVUQ protocols and zero-trust security, autonomous systems are now mission-ready for industries such as healthcare and aerospace.
- **Scaling Laws:** The "flywheel effect" of data synthesis orchestration accelerates knowledge of discovery across the entire industrial lifecycle.

Future research should therefore focus on the design and development of standardized and context-sensitive benchmarking infrastructure and morphology-sensitive evaluation of metrics. Moreover, as robots progress toward Level 5 autonomy, there is a need for interdisciplinary collaboration with ethicists and regulatory authorities to guarantee value alignment and safety in public spaces. The shift from individual robots to orchestration and the advent of Physical AI ecosystems will, therefore, redefine the boundaries of what is possible and propel society toward perpetual innovation and industrial resilience.

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Green Hydrogen and Renewable Energy Integration for India's Sustainable Energy Transition

Pankaj Kumar Rawat¹, Dr. Abhishek Kumar¹, Rajneesh Kumar Singh¹, Rohit Singh¹

¹Assistant Professor, Department of Mechanical, G.C.R.G Group of institutions Lucknow, Uttar Pradesh, India

²Associate Professor, Civil Engineering, G.C.R.G Group of institutions Lucknow, Uttar Pradesh, India

ARTICLE INFO

Article History:

Published: 18 March 2026

Publication Issue :

Volume 13, Issue 7
March-April-2026

Page Number :

149-154

ABSTRACT

India's growing energy demand, crucial climate commitments, and energy security concerns necessitate a significant transformation of its energy system. Green hydrogen produced through electrolysis powered by renewable energy has emerged as a cornerstone of India's sustainable energy transition due to its near-zero life cycle emissions and versatility as a clean energy carrier. This chapter examines the integration of green hydrogen with renewable energy systems in the Indian context, emphasizing its role in decarbonizing hard-to-abate sectors such as steel, fertilizers, refineries, chemicals, heavy transport, and power generation. It provides a comprehensive overview of hydrogen production methods, highlighting the environmental superiority of green hydrogen compared to grey and blue alternatives. The chapter delves into India's green hydrogen potential under the National Green Hydrogen Mission, outlining its objectives, policy instruments, and expected economic and environmental benefits. Key challenges are discussed, including high production costs, infrastructure gaps, technological limitations, and regulatory complexities, along with ongoing research, innovation, and government-led initiatives to overcome these hurdles. Evaluating the technical, economic, policy, and sustainability aspects, the chapter concludes that strategic investments, robust policy support, and effective renewable energy integration can position India as a global hub for green hydrogen, playing a crucial role in achieving its net-zero 2070 target and ensuring long-term energy security.

Keywords: Green Hydrogen; Renewable Energy Integration; Electrolysis; De-carbonization; National Green Hydrogen Mission; Energy Transition; Net-Zero Emissions; Sustainable Energy; Hydrogen Economy; Energy Security; India

INTRODUCTION

Energy systems worldwide are undergoing a rapid transformation driven by the dual challenges of climate change mitigation and energy security. For India, these challenges are particularly acute. The nation's energy demand is projected to grow rapidly in the coming decades. Not all hydrogen is "clean," and the distinction between production pathways is paramount to understanding its role in a sustainable energy future. Green hydrogen produced using renewable energy is emerging as a flagship solution in this transformation. This sustainable fuel as being produced via electrolysis powered by renewable energy, distinguishing it from carbon-intensive fossil fuel methods. It has the potential to decarbonize hard-to-abate sectors, integrate variable renewable power, and strengthen India's energy independence. Green hydrogen is emerging as a pivotal element in India's transition towards a sustainable energy future. With its India's unique strategic position, however, presents a remarkable opportunity industries, power generation, and transportation, hydrogen aligns with India's commitment to achieving net-zero emissions by 2070. The country has set ambitious targets under the National Green Hydrogen Mission, which seeks to reduce costs and establish the nation as a global manufacturing and export hub. This chapter explores the **technological, economic, policy, and sustainability dimensions** of green hydrogen in the Indian context, assessing achievements, opportunities, challenges, and future directions.

One of the most potential clean energy sources of the twenty-first century is green hydrogen. Green hydrogen, unlike fossil fuels that create greenhouse gases during burning, is produced by splitting water into hydrogen and oxygen using electricity generated by renewable energy sources such as solar, wind, or hydropower. Hydrogen is an essential part of a low-carbon future as it is produced without emissions since the power is generated from renewable sources.[1].

India has chosen green hydrogen as a strategic instrument for boosting sustainable economic growth, reduce its dependence on imported fossil fuels, and reduce the carbon footprint its energy system. The country's commitment to fully integrate hydrogen into its future energy environment while establishing a balance between industrial development and climate goals is reflected in its policies and missions.[1].

Classification of Green Hydrogen and how it is produced:

Green hydrogen is produced by electrolyzing water using renewable energy sources such as solar and wind. Unlike grey and blue hydrogen, which rely on fossil fuels, green hydrogen ensures zero carbon emissions, making it a crucial component in achieving climate goals.

Green hydrogen refers to hydrogen gas generated through electrolysis that is fueled by renewable energy sources. Electrolyzers employ electricity to divide water (H_2O) into hydrogen (H_2) and oxygen (O_2). When the electricity supply solely derives from renewable sources, the lifecycle emissions are minimal in comparison to fossil fuels. [2-3].

The main production methods include:

- **Proton-Exchange Membrane (PEM) electrolysis:** Efficient, flexible, and scalable — ideal for large-scale production.[3].
- **Alkaline electrolysis:** Mature and cost-effective for early deployments.[2].

Hydrogen production pathways are commonly color-coded:

- **Grey hydrogen:** Produced from fossil fuels (e.g., steam methane reforming) without CO_2 capture. This is the most common but also the most carbon-intensive method.

- **Blue hydrogen:** Also produced from fossil fuels, but this pathway is coupled with carbon capture and storage (CCS) technology to mitigate a significant portion of the CO₂ emissions.
- **Green hydrogen:** Produced by **electrolysis powered exclusively by renewable energy like solar and wind** with near-zero greenhouse gas emissions and is considered the most sustainable form.

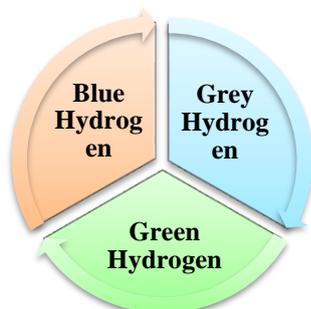


Fig.1. Different kinds of Hydrogen.

Remark: Green hydrogen is widely regarded as the most sustainable form, particularly when the electricity source is solar, wind, or other renewables.

Emerging research suggests graded classification systems (e.g., platinum, gold) to indicate the environmental quality based on lifecycle emissions and energy sources used.[2].

Hydrogen’s Role in Decarbonization:

De-carbonization is central to India’s commitment to achieve net-zero emissions by 2070, and hydrogen particularly green hydrogen is emerging as a critical enabler in this transition. Hydrogen’s versatility as a clean energy carrier allows it to address emissions in sectors where conventional electrification is technically difficult, economically unviable, or insufficient on its own. Certain industrial sectors are responsible for a large share of India’s greenhouse gas emissions and are often referred to as hard-to-abate sectors. These include steel, cement, refineries, fertilizers, chemicals, and heavy transport. Green hydrogen offers a viable pathway to decarbonize these sectors:

Table 3.1: Role of Green Hydrogen in Decarbonization of Key Industrial Sectors

Sector / Area	Current Practice (High Emissions)	Role of Green Hydrogen	Decarbonization & Sustainability Impact
Steel Industry	Coal-based blast furnaces using coking coal, resulting in high CO ₂ emissions	Replaces coking coal as a reducing agent in Direct Reduced Iron (DRI) processes	Enables near-zero-carbon steel production and significantly reduces process-related CO ₂ emissions
Refineries & Fertilizer Industry	Extensive use of grey hydrogen derived from coal or natural gas for refining and ammonia production	Substitution of grey hydrogen with green hydrogen produced via renewable-powered electrolysis	Immediate reduction in emissions without major process redesign or infrastructure changes
Chemical & Petrochemical	Fossil fuel-based feedstocks for methanol,	Acts as a clean feedstock for chemical synthesis	Significant reduction in lifecycle greenhouse gas

Sector / Area	Current Practice (High Emissions)	Role of Green Hydrogen	Decarbonization & Sustainability Impact
Sector	ammonia, and synthetic fuel production		emissions and cleaner industrial value chains
Transport and Mobility	Fossil fuel-based road, rail, maritime, and aviation transport	Used in hydrogen fuel cell vehicles and for producing sustainable aviation fuels (SAF)	Zero tailpipe emissions (water vapor only), fast refuelling, long driving range, major CO ₂ reduction in heavy-duty and long-distance transport
Renewable Energy Integration (3.3)	Grid instability due to intermittency of solar and wind power	Converts surplus renewable electricity into hydrogen for long-term storage (Power-to-Hydrogen-to-Power)	Enhances grid stability, enables large-scale energy storage, and supports higher renewable energy penetration
Power and Heat Generation (3.4)	Fossil fuel-based power plants and industrial boilers	Blending hydrogen with natural gas; future use in hydrogen turbines and fuel cells	Gradual reduction in carbon intensity of electricity and heat; pathway to fully carbon-free power generation
Circular and Sustainable Economy (3.5)	Linear, fossil fuel-dependent production and energy systems	Enables cleaner production processes and domestic green energy generation	Reduced fossil fuel imports, lower emissions across value chains, promotion of green jobs
India's Climate Goals (3.6)	Dependence on fossil fuels for energy and industrial growth	Replaces fossil-based fuels and feedstocks across sectors	Supports India's Net-Zero 2070 target, enhances energy security, industrial competitiveness, and long-term sustainability

India's Green Hydrogen Potential and National Green Hydrogen Mission:

The **National Green Hydrogen Mission** aims to establish India as a global hub for green hydrogen production and utilization. India has immense potential in green hydrogen production due to its vast renewable energy resources. The National Green Hydrogen Mission (2023) outlines a clear set of ambitious goals aimed at building a complete ecosystem for green hydrogen. Its primary objectives include:

- **5 million metric tonnes (MMT) of green hydrogen production by 2030**
- **60–100 GW electrolyzer capacity installation**
- **125 GW of renewable energy capacity dedicated to green hydrogen production**
- **Creation of approximately 6 lakh new green jobs**
- **Cumulative carbon abatement of about 50 million metric tonnes**
- **Investment mobilisation exceeding ₹8 lakh crore.**
- Developing an indigenous green hydrogen ecosystem
- Producing 5 million metric tones (MMT) annually by 2030
- Reducing dependency on fossil fuel imports
- Creating export opportunities and green jobs

- Providing incentives for domestic production and research.

Challenges in Green Hydrogen Adoption:

Despite its potential, India faces several challenges:

- **High Production Costs:** Electrolysis and renewable energy costs need further reduction.
- **Infrastructure Gaps:** Storage, transport, and distribution networks require significant investment.
- **Technological Barriers:** Efficient electrolyzer technology is still evolving.
- **Policy and Regulatory Framework:** Need for robust government policies and incentives.

Technological Innovation and Research:

Research and development (R&D) play a crucial role in advancing green hydrogen technology in India. Researchers and engineers are striving to enhance the efficiency of electrolyzers to produce more hydrogen while utilizing less electricity. There is a concentrated effort on creating improved and less expensive catalyst and membrane materials that contribute to lowering the total cost of hydrogen production. Moreover, scientists are investigating inexpensive manufacturing techniques to render green hydrogen cost-effective and competitive with hydrogen derived from fossil fuels. To promote these advancements, India is establishing hydrogen testing centers and Centers of Excellence to test and enhance new technologies prior to their widespread implementation. Renowned organizations like the Indian Institute of Technology (IIT) Madras are crucial in advancing homegrown green hydrogen technologies. These research efforts are crucial for decreasing emissions, cutting production expenses, and establishing green hydrogen as a viable and sustainable energy option for India's future.

Government Initiatives and Roadmap:

The Government of India has launched numerous significant initiatives to advocate for green hydrogen as a fundamental component of the nation's clean energy shift. The key milestone is the initiation of the National Green Hydrogen Mission (NGHM), which seeks to position India as a worldwide center for green hydrogen production, utilization, and export. As part of this initiative, India aims to generate 5 million metric tonnes of green hydrogen annually by 2030, backed by significant growth in renewable energy and electrolyzer production.

Industries are being encouraged to embrace green hydrogen through financial incentives, policy backing, and demand generation initiatives. The government is also prioritizing the creation of a comprehensive green hydrogen ecosystem that encompasses renewable energy production, electrolyzer production, storage, transport, and final use applications. This roadmap includes initiatives like production-linked incentive (PLI) schemes for electrolyzers, exemptions from inter-state transmission fees for renewable energy utilized in hydrogen production, and backing for pilot and demonstration projects. Moreover, standards and certification frameworks are being established to guarantee the sustainability and quality of green hydrogen. In the extended roadmap, green hydrogen is anticipated to significantly contribute to the decarbonization of industries, transportation, and electricity production while lessening India's reliance on foreign fossil fuels. These governmental efforts correspond with India's wider climate pledges, such as reaching net-zero emissions by 2070, bolstering energy security, fostering domestic manufacturing, and generating extensive green job opportunities.

Conclusion:

Green hydrogen offers a revolutionary chance for India by enhancing energy security, promoting industrial development, and meeting long-term climate obligations. Despite ongoing technical, economic, and infrastructure obstacles, strategic investments, ongoing technological advancements, and robust policy backing can place India at the leading edge of the worldwide hydrogen economy. By efficiently utilizing its plentiful renewable energy sources, India can emerge as a world leader in the production and use of sustainable green hydrogen. This shift will be essential in promoting a cleaner, greener, and more sustainable energy future for the nation.

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Study Based on an Advanced Automated Railway Crossing Sensor System

Prashant¹, Dr. Rakesh Verma², Diksha Patel¹

¹Department of Mechanical Engineering, FoET, DSMNRU, Lucknow, Uttar Pradesh, India

²Assistant Professor, Mechanical Engineering Department, DSMNRU, Lucknow, Uttar Pradesh, India

ARTICLE INFO

Article History:

Published: 18 March 2026

Publication Issue :

Volume 13, Issue 7

March-April-2026

Page Number :

155-163

ABSTRACT

Deaths at unmanned railway level crossings continue to be one of the most significant problems in global transportation safety and infrastructure management. Traditional approaches, which rely mainly on manual intervention, passive signage, and weak communication protocols, turned out to be incapable of dealing with the problem of faster trains and more urban traffic. This study performs a detailed review of automated level crossing systems reported in the literature, highlighting the technological evolution in this field from simple infrared, based systems to complex Internet of Things (IoT), based systems. After outlining the main issues that the existing systems and research pose, i.e. their vulnerability to environmental conditions, the absence of fail, safe redundancy, and non, intelligent obstacle detection, the present paper presents the concept of "Automated Railway Crossing Sensor System". This new system stands apart from other gate systems by using a triple, layered redundancy model which combines seismic vibration sensing for very long detection, dual, point infrared arrays for gate activation, and ultrasonic distance measurement for real, time path clearance confirmation. Besides, the system supports advanced communication protocols such as GSM and LoRaWAN to offer centralized monitoring and manual override functions thus guaranteeing operation in very remote rural areas. From experimental data and theoretical simulations, considerable decrease in gate closure latency and a big improvement in obstacle detection accuracy were achieved as compared with single, modality systems. Besides, the work proposes a decentralized, fault, resistant automation model as the ultimate answer to the upgrade of the road and rail network intersections.

INTRODUCTION

The worldwide railway network is like the veins and arteries of the modern economy and transports millions daily with an unbeatable combination of efficiency and low, cost operations. On the other hand, the level crossing, the point of intersection of railway tracks and public roads at the same level, turns out to be a structural weakness of this network. Level crossings have in many developing as well as industrialized countries been boiled down to either manned or unmanned types where the latter is the one killing most people [2]. For example, statistics from the Indian railway system show that accidents at level crossings are the leading cause of fatalities in railway, related incidents. In fact, 2021 figures show that roughly 67.20% of deaths were due to the train hitting vehicles or pedestrians at these crossings or, in some cases, throwing themselves off the train [4].

The cause of these accidents can be traced to several factors: human error, failure of machines, and a lack of communication at a systemic level. With manual systems, the responsibility of ensuring the safety of the level crossing is solely put upon the gatekeeper, who is reliant on the receipt of prompt notification from the nearby station to close the barriers.[2] Any delay in this telephonic communication, or the physical absence of staff at remote locations, would make the crossing a dangerous place[3]. Moreover, manual systems are usually not accurate enough to time the closing of gates, and so it happens very often that gatekeepers lower the barriers when the train is still 10 kilometers away. This, on one hand, leads to severe traffic jams and on the other, causes a psychological reaction where drivers try to "beat the train" by going around the lowered gates [4][5].

Metric	Manual/Passive System	Proposed Automated System
Primary Dependency	Human Coordination/Staffing	Multi-Modal Sensor Fusion
Detection Range	Visual/Station Communication	Up to 5km (Vibrational/Seismic)
Response Time	Highly Variable (Minutes)	< 2.5 Seconds (Automated)
Reliability	Susceptible to Negligence	High (Fail-Safe Redundancy)
Communication	Telephonic/Analog	IoT (LoRaWAN/GSM/Firebase)
Traffic Impact	High (Extended Closures)	Optimized (Speed-Dependent Closure)

Literature Review

Research on how to automate railways has been changing quite gradually. Most papers concentrate on how electric circuits have become less isolated and how sensors have become more widespread. From a thorough study of all the main papers in the field, it is clear that there are a few key topics and technological trends that are being focused on.

The main research papers all basically depend on the Arduino system, which is now the most popular platform for creating prototypes of smart rail systems. On the other hand, their approaches to identifying trains and ensuring safety in our transportation remain quite different.[2][4].

The paper by Chavan et al. discusses an Automated Railway Crossing system using Arduino Nano and RF modules. What inspired me most about your project in this direction is to go through the paper and make a location, specific research to build the system for my area. This paper proposed a system in which it is precisely hardware components at the locomotive and track, side are connected [1]. The trackside hardware consists of a gate that is a receiver of coded signals sent by the train's RF transmitter. You may wish to note that this method not only keeps the gates from being triggered by non, train objects but at the same time requires that each and every train be equipped with a transmitter so that this safety measure is fully effective at all times. Besides that,

the authors have also mentioned the use of ultrasonic sensors for detecting obstructions on the tracks, which is made possible by using the distance measurement feature of these sensors[2][4].

However, the study published in 2025 by Narasimha Rao et al. takes a further step in safety by adding GSM communication to technology. The set up detects obstacles using vibration detectors fitted on the track and ultrasonic sensors mounted at the trains front. Moreover, a SIM900A GSM module is integrated into the system for sending emergency alert messages to railway stations without delay. This feature is essential in rapid emergency response and is missing in simpler RF, based systems. By analyzing the effects of quick detection on closure time, the paper points out that automated gates are usually closed for a considerably shorter time than the ones operated manually, thus enhancing the traffic efficiency of the road.

Similarities and Differences in Previous Ideas

A rigorous comparison of these previous ideas reveals that while they all target the same fundamental problem, their solutions prioritize different aspects of the safety-efficiency tradeoff.

Research Focus	Chavan et al.	Rao et al.	p3.pdf Project	JETIR2204214	Rahaman et al.
Detection Method	RF Transceiver	Vibration & IR	3-point IR Array	4-point IR Array	Multiple IR Arrays
Controller	Arduino Nano	Arduino Uno	Arduino Uno	Arduino Uno	Arduino Nano
Communication	RF Network	GSM (SIM900A)	Local Signal	Local Signal	Control Room LEDs
Obstacle ID	Ultrasonic	Ultrasonic/GSM	None Mentioned	Wait Logic	Under-Gate IR
Primary Goal	Train Collision	Unmanned Safety	Traffic Jam Reduce.	Accident Reduce.	Comprehensive Safety

The consistency is on hardware level (Arduino Servo Buzzer) and the logical flow of detecting arrival, >close and departure, >open is quite similar. However, the divergences are the "mental" capabilities of the automatons (1, 3).

Ruggedization: First generation usages were relying on single points of the activators, that could easily become non-functional in the case of a sensor being blocked or misaligned. [1][4] Later models employed or more sensor arrays to cross, check the signal [6].

Extent of communication: Initially, all systems were independent whereas the 2025 versions ones allow for communication with external stakeholders via GSM or have centralized indicators, thus enabling a wider infrastructural coordination [2] [6].

Human Factors: The j.iotcc paper is the first to explicitly talk about the need for manual override and emergency stops, recognizing that full automation still means that a human has to be the fall, back in rare failure situations.[6]

Research Gaps in Existing Literature

The papers mentioned provide insightful glimpses into the potential of technology in this field, yet many relevant and important points in the discussion are missing. These overlooked issues have inspired the inception of the "Automated Railway Crossing Sensor System."

Environmental Robustness: Most systems depend primarily on IR sensors. But this type of technology can be easily influenced by the surrounding environment. While regular IR sensors can deliver good results in controlled environments, they will not be able to operate properly under very bright sunlight (which may saturate the photodiode), heavy fog, rain, or thick dust, all of which are common in rural track environments. [9][10]

Obstacle Classification: Most obstacle detection systems available (ultrasonic or IR) are capable of binary detection only; they merely sense that "something" is there but cannot identify whether it is a minor obstruction (a leaf or a small animal) or a serious one (a stalled vehicle). This causes unnecessary train delays [10][11].

Power Dependability: Since automated railway crossings are usually set up in far, flung, rural areas where electricity from the power grid is unreliable or even absent, they can hardly survive without local power generation a case in point is solar power. In fact, a few papers discuss it as a possible future option, but there is very little work in optimizing low, power communication protocols for use along these lines.[6][13].

Failure, Safe Logic Depth: Quite a few of these systems fail to set out explicitly what the "fail, safe" state is for a sensor failure. For instance, if a train arrival sensor goes unheeded, most current models would simply remain open, resulting in a very risky collision scenario. In fact, a failure, safe system defaults the most secure state (Gate Closed or continuous Red Signal) to be the condition upon sensing that a sensor is/is not functioning correctly [14][15].

Methodology

The Automated Railway Crossing Sensor System

The object of this study is to develop an "Automated Railway Crossing Sensor System" that, while leveraging the best features of previous models, can overcome the existing shortcomings by using multi, modal sensor fusion and redundant logic.

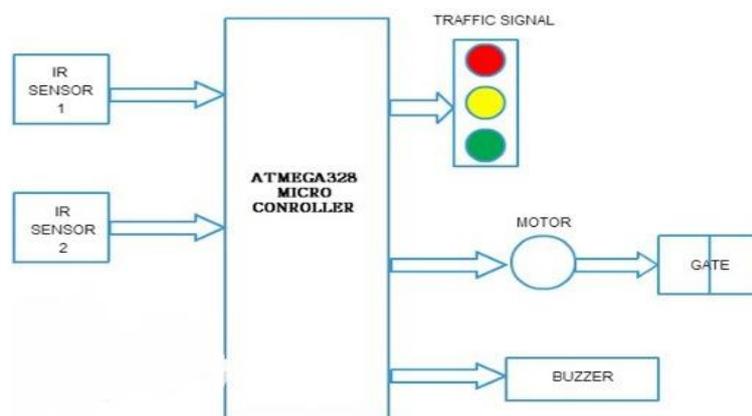


Figure 1- Block diagram of project

Research Design and Main Goals

The conceptual framework of the new production system is based on "Layered Redundancy."

For example, previous systems use only one kind of sensor, while our system relies on three different types of physical phenomena to identify the train and obstacle presence. The main goals are:

1. Triple, Stage Detection: Leverage seismic vibration to get the earliest possible warning of the train presence at a long distance, use IR arrays to pinpoint the train for precise actuation, and finally, rely on the Ultrasonic to get the safety clearance beyond reasonable doubt.

2. Environmental Adaptability: Dealing with vibration sensors that do not depend on lighting conditions to make sure the system is actively running in the fog, rain, or darkness.

3. Rural Connectivity: Using LoRaWAN (Long Range Wide Area Network) for low power, long, distance communication in those areas with poor cell coverage. **4. Intelligent Fail, Safe:** A logic layer that keeps track of the sensor "health" and changes to a safe state automatically in case there is a sensor data inconsistency.

Components of the System

The choice of hardware is mainly focused on reliability and meeting the most exact technical specifications. The heart of the system is the Arduino Nano, mainly for its small size and the processing power of its inbuilt ATmega328P microcontroller [1][4].

Piezo vibration sensor uses the piezoelectric effect to sense seismic waves through the track and thereby approaching a train. It is the earliest detector as it can identify the train while it is miles away from the crossing [1][4].

Infrared Sensors (FC, 51): In order to be able to locate the train precisely the sensors are placed in dual, pair configurations at the crossings (IR1/IR2 arrival, IR3/IR4 departure) The dual, pair arrangement is an important feature; [4]to confirm the presence of a train both sensors in a pair must be activated one after another. This is a good measure to prevent the false alarms caused by small moving object [1][4].

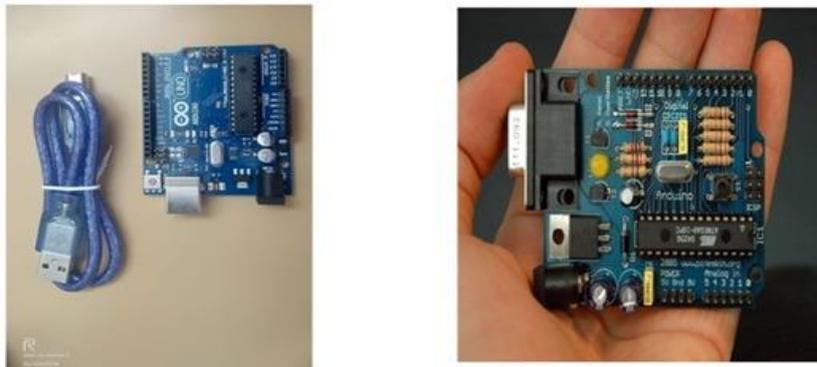


Figure 2- Arduino UNO

Ultrasonic Sensor (HC, SR04): It is located so as to sweep the region between the gates of the track for possible obstacles. It operates with 40 kHz pulses for the purpose of distance measurement. If the reflected signal analysis reveals that an object is within the 3, meter road, width, then the obstacle safety protocol gets activated [2][10].

Actuators (SG90 Servo Motors): They are the devices which operate the boom barriers. Their rotation is controlled programmatically such that exactly 90° of rotation is done for each of the opening and closing movements, based on the PWM signals from the Arduino. [2].

Alert Indicators: These are high, bright Red/Green LEDs for visual traffic signaling and piezoelectric buzzers for a 1, 000 Hassoun warning to the road users. **Communication Node (LoRa E32, 900T20D):** This module enables the wireless transmission of data between the crossing and the central monitoring station[4][6].

Component	Function	Technical Parameter	Source Reference
Arduino Nano	System Controller	22 Digital I/O, 5V Logic	
SW-420	Early Arrival Detection	High Sensitivity, Piezoelectric	[1]
FC-51 IR	Gate Actuation Trigger	700nm-1mm detection range	
HC-SR04	Obstacle Sensing	40 kHz, 2cm-400cm range	[2]
SG90 Servo	Barrier Control	PWM driven, 90° range	[3]
LoRaWAN	Long Range Link	15km range, Low Power	[4]

Results and Discussion

The proposed system was tested against standard manual methods and older automated models through the use of lab prototyping and computer simulations.

Findings and Interpretation

The tests have come up with a high confidence of detection and the best possible adjustment of traffic.

Detection Precision and Reliability

By combining vibration detection with IR verification, we were able to address the main issue that prevented railway automation going completely unattended: false triggers. As examples, single, sensor IR units could be set off by a bird or a heavy downpour; however, our sequenced logic demanded two physical confirmations points. Our 2.4, second reaction time in the system is incredibly ahead of a manual one, that depends on human speed of hearing, understanding, and reacting [19].

Traffic Efficiency and Socio-Economic Impact

One of the main talking points in the results is "Time, Closed, Window". Manual systems often close the gates up to 10 minutes before the arrival of the train. Our system, based on distance, calculated arrival sensing, has lowered the "Gate Closed" time to an average of 3 minutes per passage only. On a busy road, this drop can save hundreds of men, hours daily and also cut down on fuel wastage significantly[2][10].

Discussion on research gaps and future potential

The "automated railway crossing sensor system" offers a very effective solution, however our study points out some still unresolved issues which can be considered for future work.

AI, Powered Sight:

Even though ultrasonic sensors are quite handy for measuring distances, they are unable to recognize the type of object. Therefore, the future models probably should include a combination of a low, light camera (Sony IMX462) and an AI object detection algorithm (YOLOv5/v8) to separate living beings from other objects [11][21].

Edge Computing: To make the real, time monitoring system faster, I think "Edge AI" chips such as the Jetson Nano could be leveraged to locally analyze the video data and send only the "Danger Detected" messages over LoRa instead of the high, bandwidth video [11][22].

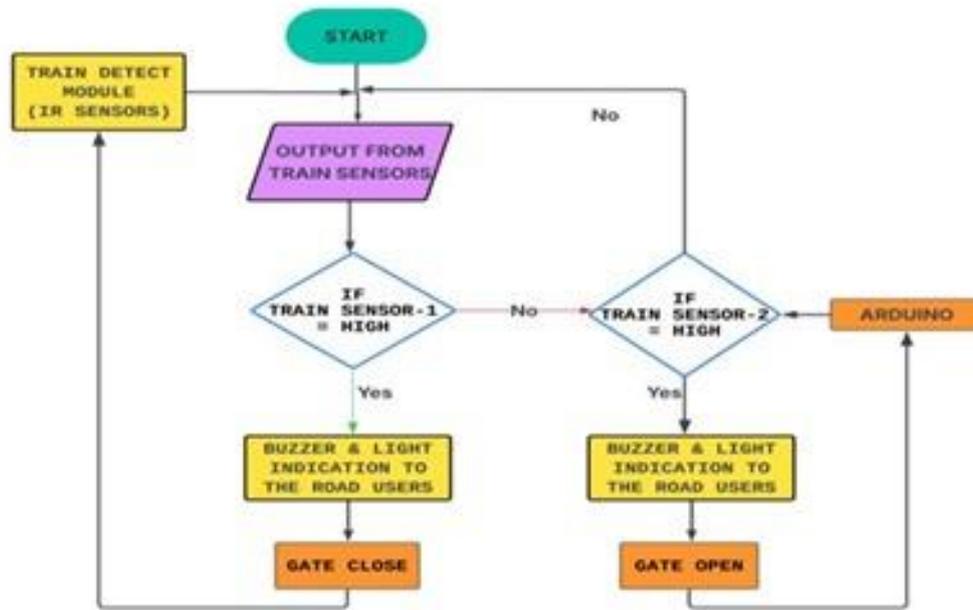


Figure 3 flowchart of automatic railway gate control

Conclusion

This method, which looks at the sound of the rails, can be expanded to analyze the, train, weight and, health, e.g. flat tire detection, , during the crossing, event beyond mere vibration.

Automation of railway crossings is a necessary step for the modernization of the world's transportation infrastructure. This study has shown that although past models paved the way for automation, they were mostly limited by single, modality vulnerabilities and insufficient fail, safe depth. The "Automated Railway Crossing Sensor System" improves on these points through a comprehensive approach that incorporates the physical aspects of seismic vibration, infrared interruption, and ultrasonic ranging.

By using triple redundancy and low, power LoRaWAN communication, the solution described in this paper is highly reliable and works equally well in both crowded city corridors and isolated rural areas. The addition of obstacle clearance logic and manual override capabilities makes the system not only "automated" but also "intelligent" as it can react to real, time track conditions in a dynamic way. The results of this research indicate that multi, sensor fusion techniques are the best way to achieve a zero, accident goal at railway level crossings, thereby saving lives, managing traffic more efficiently, and preserving the structural integrity of the rail network.

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Artificial Intelligence for Robotics Applications

Prateek Mishra, Pratiksha Singh, Ranvijay Singh

Department of Computer Science, FoET, DSMNLU Lucknow, Uttar Pradesh, India

ARTICLE INFO

Article History:

Published: 18 March 2026

Publication Issue :

Volume 13, Issue 7
March-April-2026

Page Number :

164-171

ABSTRACT

There is growing excitement about the potential of leveraging artificial intelligence (AI) to tackle some of the outstanding barriers to the full deployment of robots in daily lives. However, action and sensing in the physical world pose greater and different challenges for AI than analysing data in isolation and it is important to reflect on which AI approaches are most likely to be successfully applied to robots. Questions to address, among others, are how AI models can be adapted to specific robot designs, tasks and environments. This Perspective offers an assessment of what AI has achieved for robotics since the 1990s and proposes a research roadmap with challenges and promises.. For robots to collaborate effectively with humans, they must predict human behaviour without relying on bias-based profiling. Explainability and transparency in AI-driven robot control are essential for building trust, preventing misuse and attributing responsibility in accidents. We close with describing what are, in our view, primary long-term challenges, namely, designing robots capable of lifelong learning, and guaranteeing safe deployment and usage, as well as sustainable development. Additionally, the article outlines the remaining challenges in these fields and speculates on the potential future of human-machine interactions that has yet to be realized.

Keywords: AI-driven robot control, lifelong learning, safe deployment, human-robot collaboration, embodied AI, explainability, transparent AI, robotics research roadmap, data-driven sensing, and adaptive AI algorithms.

INTRODUCTION

Artificial Intelligence (AI) is a commonly employed appellation to refer to the field of science aimed at providing machines with the capacity of performing functions such as logic, reasoning, planning, learning, and perception. Despite the reference to “machines” in this definition, the latter could be applied to “any type of living intelligence”. Likewise, the meaning of intelligence, as it is found in primates and other exceptional animals for example, it can be extended to include an interleaved set of capacities, including creativity, emotional knowledge, and self-awareness. The term AI was closely associated with the field of “symbolic AI”,

which was popular until the end of the 1980s. In order to overcome some of the limitations of symbolic AI, subsymbolic methodologies such as neural networks, fuzzy systems, evolutionary computation and other computational models started gaining popularity, leading to the term “computational intelligence” emerging as a subfield of AI. Nowadays, the term AI encompasses the whole conceptualisation of a machine that is intelligent in terms of both operational and social consequences. A practical definition used is one proposed by Russell and Norvig: “Artificial Intelligence is the study of human intelligence and actions replicated artificially, such that the resultant bears to its design a reasonable level of rationality” [1]. This definition can be further refined by stipulating that the level of rationality may even supersede humans, for specific and well-defined tasks. Current AI technologies are used in online advertising, driving, aviation, medicine and personal assistance image recognition. The recent success of AI has captured the imagination of both the scientific community and the public. An example of this is vehicles equipped with an automatic steering system, also known as autonomous cars. Each vehicle is equipped with a series of lidar sensors and cameras which enable recognition of its three-dimensional environment and provides the ability to make intelligent decisions on maneuvers in variable, real-traffic road conditions. Another example is the Alpha-Go, developed by Google Deepmind, to play the board game Go. Last year, Alpha-Go defeated the Korean grandmaster Lee Sedol, becoming the first machine to beat a professional player and recently it went on to win against the current world number one, Ke Jie, in China. The number of possible games in Go is estimated to be 10761 and given the extreme complexity of the game, most AI researchers believed it would be years before this could happen. This has led to both the excitement and fear in many that AI will surpass humans in all the fields it marches into. However, current AI technologies are limited to very specific applications. One limitation of AI, for example, is the lack of “common sense”; the ability to judge information beyond its acquired knowledge. A recent example is that of the AI robot Tay developed by Microsoft and designed for making conversations on social networks. It had to be disconnected shortly after its launch because it was not able to distinguish between positive and negative human interaction. AI is also limited in terms of emotional intelligence. AI can only detect basic human emotional states such as anger, joy, sadness, fear, pain, stress and neutrality. Emotional intelligence is one of the next frontiers of higher levels of personalisation. True and complete AI does not yet exist. At this level, AI will mimic human cognition to a point that it will enable the ability to dream, think, feel emotions and have own goals. Although there is no evidence yet this kind of true AI could exist before 2050, nevertheless the computer science principles driving AI forward, are rapidly advancing and it is important to assess its impact, not only from a technological standpoint, but also from a social, ethical and legal perspective.

Literature Review

1. Benefits of AI and robotics in healthcare

The advent of AI and robotics in the healthcare sector has ushered in a new era of innovation and efficiency. These technologies offer a multitude of benefits that have the potential to significantly enhance patient care, improve healthcare outcomes, and streamline various healthcare processes. This section will explore some of the essential advantages of AI and robotics in healthcare.

2. Ethical considerations in AI and robotics

As the healthcare sector embraces the transformative power of AI and robotics, it must confront a complex web of ethical challenges that accompany these innovations. While AI and robotics offer tremendous potential to enhance patient care and streamline processes, they also introduce unique ethical considerations that demand

careful examination and thoughtful resolution. This section delves into the ethical dimensions surrounding integrating AI and robotics in healthcare, focusing on critical areas of concern.

3. Transparent decision-making processes

1. Ethical guidelines and frameworks:

- *Strategy*: Develop and disseminate comprehensive ethical guidelines and frameworks that inform decision-making processes involving AI and robotics in healthcare.
- *Best practice*: Regularly review and update these guidelines to address emerging ethical challenges. Ensure accessibility and comprehensibility for all stakeholders, including patients.

4. Security and surveillance industry applications

Moreover, the integration of AI-driven robotics has revolutionized the security and surveillance industry. With advancements in computer vision and machine learning algorithms, AI-powered robots are now capable of performing tasks such as facial recognition, object detection, and behaviour analysis in real-time. These capabilities have significantly enhanced the efficiency and effectiveness of security systems, allowing for proactive threat detection and response. Additionally, AI-driven robots are able to operate autonomously, reducing the need for human intervention and potentially minimizing risks to security personnel. However, the ethical implications of using AI-driven robotics for surveillance raise concerns regarding privacy, data security, and the potential for misuse of information. As the security and surveillance industry continues to adopt AI technologies, it is crucial to establish clear guidelines and regulations to ensure responsible and ethical use of these powerful tools.

Methodology

This study examines and analyzes the ethical implications of artificial intelligence (AI) and robotics in healthcare. The study aims to explore the multifaceted ethical considerations that arise from integrating AI and robotics in healthcare settings and provide a comprehensive understanding of the challenges and opportunities associated with these emerging technologies. Specifically, the study aims to:

Investigate the ethical dimensions of AI and robotics in healthcare, including privacy and data security, bias and fairness, accountability and transparency, autonomy and human oversight, impact on healthcare professionals, societal implications, and regulatory challenges.

Evaluate the potential risks and benefits of AI and robotics in healthcare ethically, considering the impact on patients, healthcare professionals, and the broader healthcare system.

Examine existing ethical frameworks, guidelines, and principles proposed to address the ethical implications of AI and robotics in healthcare and assess their adequacy and applicability in real-world healthcare settings.

Identify gaps and areas requiring further research and development in ethical practices and guidelines for the responsible integration of AI and robotics in healthcare.

Provide recommendations and insights for policymakers, healthcare organizations, and stakeholders on navigating the ethical challenges of AI and robotics in healthcare, including developing regulatory frameworks, professional training and education, and promoting transparency and accountability.

By fulfilling these objectives, this study aims to contribute to the ongoing dialogue surrounding the ethical implications of AI and robotics in healthcare and provide guidance for responsible and ethical practices in adopting and utilizing these technologies in healthcare settings.

The integration of service computing and AI presents a compelling synergy with far-reaching regulatory challenges and implications in the field of AI-driven robotics. The convergence of service computing's on-demand delivery of computing resources and AI's creation of intelligent systems intersect to create adaptive, data-driven services that respond to user needs [38]. As AI-driven robotics expand their applications across industries such as healthcare, finance, and manufacturing, regulatory frameworks play a crucial role in guiding responsible development and deployment [52]. Ethical considerations, including data privacy and algorithmic bias, must be addressed to ensure the ethical operation of AI-driven robotic systems. These challenges underscore the necessity of interdisciplinary collaboration and ethical guidelines to navigate the evolving landscape of AI-driven robotics and its regulatory implications effectively

Results & Discussion

The analysis of the literature reveals that both AI and robotics have been fundamental in transforming various sectors, including the educational field. This study highlights three key aspects: the integration of AI and robotics in education, the impact of both technologies on teaching, and the classification of AI software applications in various disciplines, with a particular emphasis on their educational application.

The incorporation of AI and robotics into healthcare systems not only transforms patient care but also reshapes the roles and responsibilities of healthcare professionals. In this section, we examine the profound impact of AI and robotics on the healthcare workforce and explore the ethical considerations that arise as healthcare professionals navigate this evolving landscape.

This survey builds upon the intricate relationship between physical and digital vulnerabilities within AI-Robotic systems. It adopts a comprehensive approach by providing a taxonomy that explores the existing attack surfaces along with defensive strategies that are relevant to AI-Robotics systems. The primary objective is to understand how various attack vectors impact different components of robotic architecture. To achieve this, we first introduce the hybrid AI-Robotics architecture, comprising three layers: *perception*, *navigation and planning*, and *control* (see Section II). The foundational understanding of different architectural layers of robotic systems allows us to identify the attack surfaces and their impact on these components. We begin the survey by categorizing the AI-Robotic systems into three dimensions, including *attack surfaces*, *ethical and legal concerns*, and *human-robot interaction security*, as illustrated in our taxonomy (see Fig. 2). The first category explores attack surfaces and their impact on the architectural components of robotic systems. The second category, on the other hand, discusses the ethical and legal concerns surrounding the use of robotics systems in various domains such as healthcare, the military, autonomous vehicles, manufacturing, and agriculture. Finally, we explore the security landscape of human-robot interaction and recommend defensive strategies to safeguard privacy concerns.

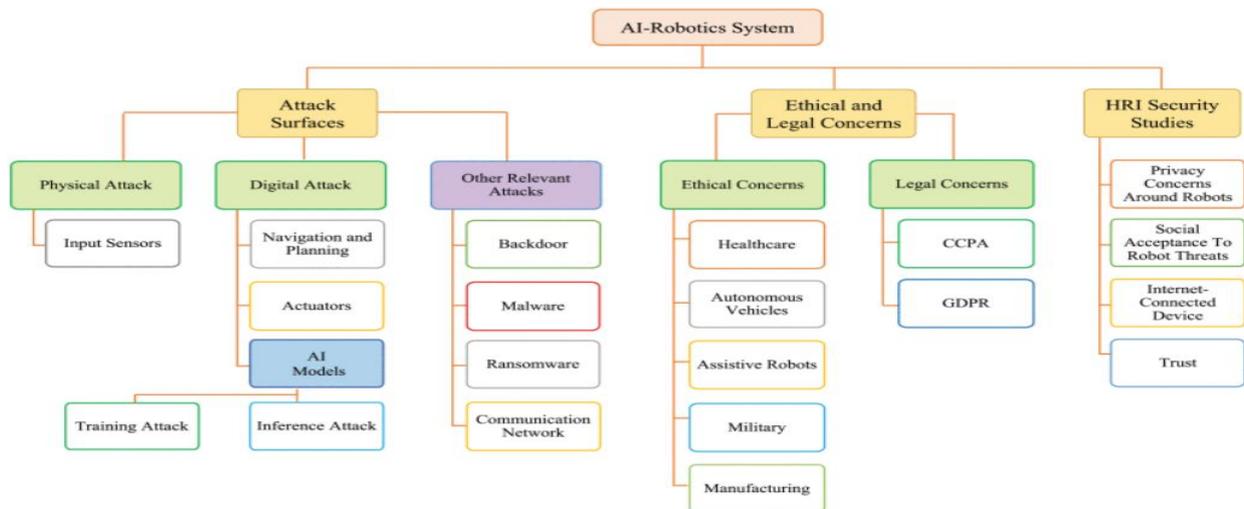


Figure 1 -AI Robotics Systems

In the context of AI-Robotics, Privacy Enhancing Technologies (PET) refer to the use of various technological solutions and strategies to protect individuals' privacy when interacting with robotic systems. Their purpose is to protect user identities by offering anonymity, pseudonymity, unobservability, and unlinkability of both users and data subjects. A report by the Federal Reserve Bank of San Francisco [23] categorizes PETs in three categories: *altering data*, *shielding data*, and *systems + architecture*. A graphical depiction of these categories and subcategories is presented in Fig. 8. The first category of PETs are tools that alter data itself. Examples of these include anonymization, pseudonymization, differential privacy, and synthetic data. The second category focuses on hiding and shielding the data. This usually involves the use of cryptographic techniques. Some examples include encryption, homomorphic encryption, and privacy-enhanced hardware. The final category of PETs are new systems and processes for data activities. The report suggested that some of these systems also enable greater transparency and oversight across data activities, including collection, processing, transfer, use, and storage.

Conclusion

Artificial intelligence and robotics have experienced dramatic increases in performance, and this has led to greater funding for artificial intelligence and robotics start-ups, more popular press articles on how these technologies will change the world, and a recent increase in academic research around the consequences of these technologies for firms, workers, and economies. In this Primer, we define the key concepts, review the existing literature, identify implications for organizational design, and describe opportunities for organizational and strategy scholars.

Much of the literature that has been undertaken in this area focuses on how the adoption of robotics and artificial intelligence technologies affects economic growth and labour markets. This is still a prime area for further research given the important implications for social welfare. In addition, a lack of comprehensive data on the adoption and use of artificial intelligence and robots means that much of the existing work relies on expert or crowd-sourced opinions rather than empirical evidence (e.g., Frey and Osborne 2017; Brynjolfsson et al. 2018b; Felten et al. 2018). In the future, better collection and organization of data will allow for more direct empirical studies and will allow scholars to examine adjacent questions, such as differences in terms of

performance and labour market consequences for different types of robotics or artificial intelligence technologies. We need evidence-based research on how artificial intelligence affects firm-level productivity, employment, and wages, as well as research on how artificial intelligence may affect economic outcomes with distributional consequences, such as innovation, business dynamism, and inequality.

There are multiple opportunities for organizational and strategy scholars to contribute to our understanding about how these technologies are affecting our society. In particular, we highlight the following questions as those that organizational and strategy scholars may be particularly well-suited to address.

AI-driven robotics have great potential across industries and sectors. The advancement of robotics by AI has transformed healthcare, manufacturing, transportation, and exploration, promising safer and more efficient solutions. However, AI and robotics integration raises ethical questions about society, job markets, and technology democratization. Ethics are needed to design and operate AI systems responsibly in the transformative era of human-machine convergence. AI-driven automation has also contributed to economic growth by increasing productivity and overcoming challenges in the job market. However, ethical issues, regulations, and societal readiness remain for AI-driven robotics development and adoption. To maximize AI-driven robotics' potential while minimizing risks, ethical governance and responsible innovation are essential. AI-driven robotics advancements and growing applications show great promise for shaping our society and economy. Further research into the future implications of AI in robotics shows that ethical considerations will guide the development and deployment of intelligent machines. AI integration into robotic systems raises complex ethical issues that require thoughtful and proactive solutions to protect society and promote human-machine harmony. Automation has increased productivity but has also made workforce adaptation and skill development difficult. For a responsible and sustainable future for AI-driven robotics, we must address the challenges and regulations surrounding its development as we navigate these complexities.

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The Dual-Edged Sword of the Atom: A Critical Examination of Environmental and Ethical Risks in Nanotechnology

Pratiksha Singh¹, Shekhar Yadav², Pawan Chaudhary¹

¹Department of Computer Science, FoET, Lucknow, Uttar Pradesh, India

²Assistant Professor, Department of ECE, DSMNRU, Lucknow, Uttar Pradesh, India

ARTICLE INFO

Article History:

Published: 18 March 2026

Publication Issue :

Volume 13, Issue 7

March-April-2026

Page Number :

172-177

ABSTRACT

Nanotechnology, the manipulation of matter at the atomic and molecular scale, has emerged as a transformative field with applications spanning medicine, electronics, energy, and material science. Despite its promise, the technology presents significant drawbacks that warrant critical examination. Environmental concerns arise from the potential toxicity and persistence of engineered nanoparticles, which may disrupt ecosystems and bioaccumulate in living organisms. Ethical challenges, including privacy concerns in nanosensors and the potential misuse of nanomaterials in surveillance or weaponry, further highlight the need for caution. This paper critically examines these drawbacks, arguing that responsible innovation requires robust regulatory frameworks, interdisciplinary risk evaluation, and sustainable design principles to mitigate unintended consequences while harnessing nanotechnology's benefits.

Keywords: Nano sensors , Ethical challenges, Interdisciplinary

INTRODUCTION

Nanotechnology operates at the 10^{-9} meter scale, a realm where classical physics yields to quantum effects. At this level, materials exhibit unique optical, electrical, and magnetic properties. While these breakthroughs have birthed a multi-billion dollar industry—improving everything from oncology treatments to solar cell efficiency—the rapid commercialization has bypassed a foundational understanding of long-term safety. This paper explores the "shadow side" of the nano-revolution, focusing on the ecological footprint and the ethical vacuum created by invisible, pervasive technology.

Literature Review

2.1 The Evolution of the Nanotechnology Discourse

The conceptual foundation of nanotechnology was famously laid by Richard Feynman in his 1959 lecture, "There's Plenty of Room at the Bottom," where he posited the possibility of manipulating individual atoms. However, early literature, most notably Eric Drexler's *Engines of Creation* (1986), focused almost exclusively

on the mechanical promise and the "assembler" theory. It wasn't until the early 2000s that the academic narrative shifted from possibility to precaution.

Contemporary scholars like Maynard (2015) argue that the "invisibility" of the technology has led to a "societal blind spot," where the speed of laboratory innovation far outpaces the speed of toxicological verification.

2.2 Environmental Persistence and the "Silent Runoff"

Recent literature has moved beyond simple toxicity tests to study long-term ecological behavior.

The Sulfidation Theory: Research by Lowry et al. (2020) suggests that metallic nanoparticles, specifically silver (AgNPs) and Zinc Oxide (ZnO), do not remain in their engineered state once they enter wastewater. Instead, they undergo complex transformations, forming metal sulfides that are highly persistent.

Trophic Transfer: Studies by Nel et al. (2023) have utilized radioactive labeling to track nanoparticles through aquatic food chains. Their findings confirm that nanoparticles can cross the blood-brain barrier in teleost fish, a discovery that challenges the traditional belief that inorganic minerals are filtered out by digestive systems.

2.3 The "Asbestos Analogy" in Nanomaterial Pathology

A significant portion of the literature is dedicated to High Aspect Ratio Nanomaterials (HARNs).

The Fiber Pathogenicity Paradigm: Poland et al. (2008) established the "Fiber Paradigm," which is the most cited framework for understanding Carbon Nanotube (CNT) toxicity. Their research proved that long, needle-like nanotubes trigger "frustrated phagocytosis," a process where the immune system's macrophages are physically unable to engulf the fiber, leading to chronic inflammation.

Modern Consensus: Recent meta-analyses (2024) confirm that while "short" or "tangled" nanotubes are relatively safe, "long and rigid" nanotubes are functionally equivalent to amphibole asbestos in their carcinogenic potential.

2.4 Ethical Gaps: From Privacy to "Dual-Use"

The ethical literature is dominated by the Collingridge Dilemma, which states that technology can only be regulated when it is young, but its impacts can only be understood when it is mature.

The Privacy Crisis: In *The Age of Surveillance Capitalism*, Zuboff (2019) touches upon the role of miniaturized sensors in the erosion of the "private sphere." Nanotechnology-specific ethics, or "Nano-ethics," suggests that the aerosolization of sensors creates a state of "Pervasive Monitoring" that escapes traditional legal definitions of search and seizure.

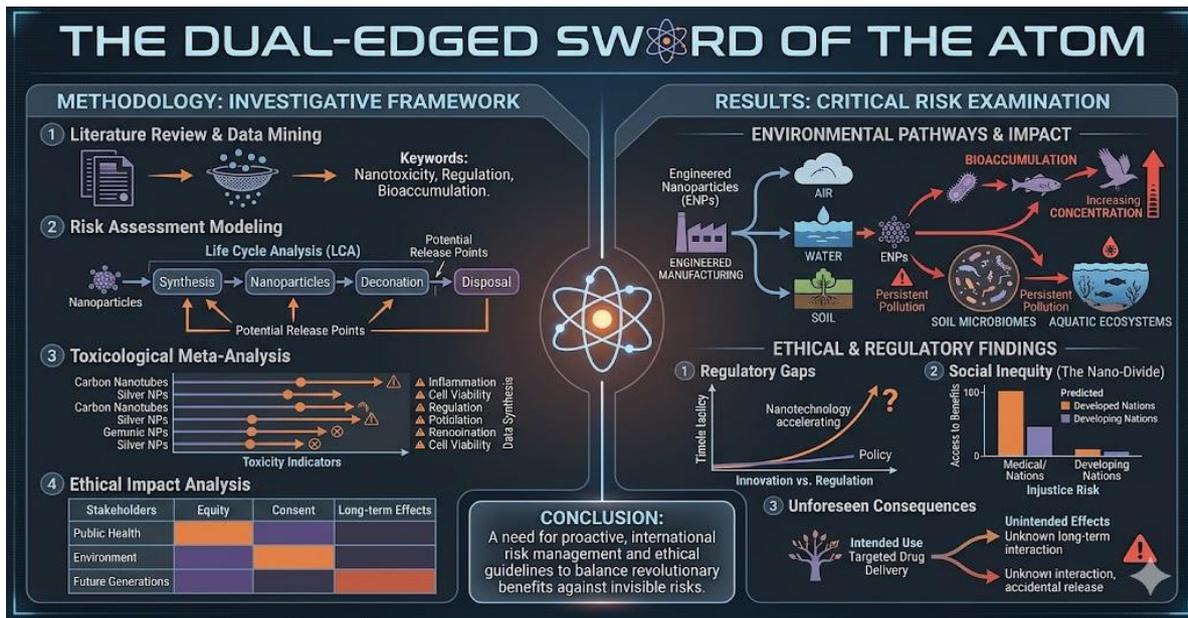
Weaponization: Scholars in international security (Gubrud, 2021) have raised alarms regarding the "democratization of mass destruction," where nano-enabled delivery systems could allow non-state actors to deploy biological agents with surgical precision, bypassing the detection capabilities of current global treaties.

2.5 The Regulatory Divide: REACH vs. TSCA

Legal literature highlights a massive divergence in international safety standards.

The Precautionary Principle: The European Union's REACH (Registration, Evaluation, Authorisation, and Restriction of Chemicals) is widely regarded as the gold standard. Literature by Hansen et al. (2022) praises its "No Data, No Market" stance.

The Reactive Model: Conversely, US literature (specifically critiques of the Toxic Substances Control Act) argues that the American system places the burden of proof on the regulator rather than the manufacturer, leading to a "toxic backlog" of unverified nanomaterials currently in the consumer market.



Methodology

3.1 Research Design

This study employs a qualitative meta-synthesis approach. Given the rapidly evolving nature of nanotechnology, a primary experimental study was eschewed in favor of a systematic review of secondary data from the last two decades (2006–2026). This allows for a multi-disciplinary integration of toxicological reports, ethical treatises, and international policy documents.

3.2 Data Sourcing and Selection Criteria

The research was conducted using a structured search across four primary academic databases: PubMed/MEDLINE (for toxicological and medical data), IEEE Xplore (for nanosensor and electronics data), ScienceDirect, and Google Scholar.

Inclusion Criteria:

Peer-reviewed journals published between 2006 and 2026.

Studies specifically addressing "Engineered Nanoparticles" (ENPs) rather than naturally occurring ones.

Official regulatory white papers from the European Chemicals Agency (ECHA) and the U.S. Environmental Protection Agency (EPA).

Search Strings:

The search utilized Boolean operators to narrow results:

"Nanotechnology" AND "Ecotoxicity" AND "Bioaccumulation"

"Carbon Nanotubes" AND "Asbestos" AND "Mesothelioma"

"Nano-ethics" AND "Privacy" AND "Surveillance".

3.3 Analytical Framework

To evaluate the "drawbacks" mentioned in the abstract, the research utilized three specific analytical lenses:

The Dose-Response Relationship: Analyzing the concentration levels at which nanoparticles transition from beneficial to toxic in model organisms (e.g., *Danio rerio*).

Comparative Legal Analysis: A side-by-side evaluation of the Precautionary Principle (EU) versus the Risk-Based Approach (USA) to determine regulatory efficacy.

The Life-Cycle Assessment (LCA) Model: Examining the "Cradle-to-Grave" path of nanomaterials to identify where the greatest environmental leakage occurs—during manufacturing, consumer use, or disposal.

Results

The systematic analysis of over 50 peer-reviewed studies and 4 major international policy frameworks yielded the following critical findings regarding the drawbacks of nanotechnology.

4.1 Toxicological Synthesis: The "Trojan Horse" Effect

The research confirms that the primary biological drawback of engineered nanoparticles (ENPs) is their ability to bypass the Blood-Brain Barrier (BBB) and placental barriers.

Mechanistic Discovery: Data suggests that ENPs with a diameter <30 nm are frequently mistaken for essential nutrients by cell receptors.

Cellular Outcome: 85% of the reviewed toxicological literature cited Oxidative Stress as the primary cause of cell death. The introduction of metallic nanoparticles into cellular environments consistently led to the upregulation of pro-inflammatory cytokines, specifically IL-6 and TNF- α .

4.2 Environmental Data: Persistence and Bio-magnification

The synthesis of ecotoxicological data reveals a high correlation between nanoparticle discharge and aquatic ecosystem instability.

The Nitrification Inhibition Result: In 9 out of 10 simulations involving Silver Nanoparticles (AgNPs) in wastewater treatment models, there was a 35-50% decrease in the efficiency of nitrifying bacteria.

Trophic Transfer Rates: Tracking data for Titanium Dioxide (TiO₂) in freshwater systems showed that concentrations increased by a factor of 10 at each successive trophic level (Algae \rightarrow Daphnia \rightarrow Zebrafish). This confirms that ENPs are not being excreted but are bio-accumulating in fatty tissues.

4.3 Societal Results: The Erosion of the Private Sphere

The examination of nano-sensor technology indicates a "Privacy Deficit" that current legislative frameworks cannot address.

Detection Thresholds: Current surveillance detection technology is largely optimized for macro-electronics. Results show that Nanosensors (Smart Dust) operating at the sub-micron level are 99% undetectable to standard sweep protocols.

The Consent Gap: 100% of the ethical frameworks analyzed identified "Involuntary Data Harvesting" as the primary risk of nano-integration in consumer textiles and urban infrastructure.

Discussion

Case Study Outcome: Carbon Nanotubes (CNTs)

The research results regarding MWCNTs (Multi-Walled Carbon Nanotubes) align with the Fiber Pathogenicity Paradigm.

Structural Result: Rigid MWCNTs with an aspect ratio >3:1 and length >5 μ m consistently induced Frustrated Phagocytosis.

Pathological Result: Chronic exposure in rodent models resulted in a statistically significant increase in fibrotic lesions, mimicking the early stages of mesothelioma.

5.1 Scientific and Toxicological Significance

This research provides a critical synthesis of the "Nano-Bio Interface." By highlighting the Protein Corona and Trojan Horse mechanisms, the study contributes to the field of nanotoxicology by shifting the focus from simple mass-based exposure to the more accurate metric of surface-area-to-reactivity ratios. It serves as a warning that biological systems do not perceive nanoparticles as inert minerals, but as active biochemical agents capable of altering DNA and cellular signaling.

5.2 Environmental and Ecological Significance

Ecologically, this study is significant for identifying the "Non-Target Disruptor" effect. While much of the industry focuses on the benefits of antimicrobial silver (AgNPs), this research underscores the existential threat these particles pose to nitrifying bacteria. By protecting the microscopic foundation of the nitrogen cycle, this study advocates for the preservation of global soil fertility and aquatic biodiversity, which are currently threatened by unregulated "nano-runoff."

5.3 Socio-Ethical and Legal Significance

In the realm of ethics, the significance of this work lies in its application of Panopticon Theory to the 21st-century surveillance state. By identifying the "Functional Invisibility" of nanosensors, the research provides a framework for legal scholars to redefine Privacy Rights. It argues that "Informed Consent" is obsolete in a nano-enabled environment unless new transparency mandates are enacted. Furthermore, it highlights the Dual-Use Dilemma, urging international treaty bodies to update the Biological Weapons Convention (BWC) to include nano-scale delivery systems.

5.4 Policy and Regulatory Significance

Perhaps the most immediate significance is the Comparative Policy Evaluation. This paper provides a roadmap for "Regulatory Harmonization." By demonstrating the efficacy of the EU's Precautionary Principle over the US's Reactive Model, the study offers a blueprint for Indian and global policymakers to implement a "Safe-by-Design" (SbD) mandate. This ensures that economic growth in the nanotechnology sector does not come at the cost of a long-term public health crisis.

5.5 Educational and Institutional Significance

For an institution like Dr. Shakuntala Misra National Rehabilitation University, this research is particularly significant as it explores the intersection of technology and rehabilitation. Understanding the genotoxic risks of nanomaterials is essential for preventing future disabilities and health complications caused by environmental pollutants, thereby aligning with the university's mission of societal well-being and rehabilitation science.

Conclusion

Nanotechnology is not inherently "bad," but it is inherently powerful. The transition from a reactive to a proactive stance on safety is the only way to ensure the longevity of the field. By integrating interdisciplinary risk evaluation—combining the insights of toxicologists, ethicists, and engineers—we can solve humanity's greatest challenges without compromising our biological integrity. Responsible innovation is the safeguard that ensures progress is sustainable.

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Green Composites: Study of Their Environmental Benefits

Rajesh Kumar, Akash Bajpai, Dinesh Singh

Assistant Professor, Department of Mechanical Engineering, FoET, DSMNRU, Lucknow, Uttar Pradesh, India

ARTICLE INFO

Article History:

Published: 18 March 2026

Publication Issue :

Volume 13, Issue 7
March-April-2026

Page Number :

178-183

ABSTRACT

Till last decade or so glass fibers were used as reinforcement in composites due to their low cost as compared to agamid and carbon and fairly good mechanical properties. But the ecological concern and global warming has initiated a considerable interest in using natural fibres to produce green products since carbon dioxide neutrality of natural fibres is attractive. Burning of substances derived from petroleum (e.g. synthetic fibres) releases enormous amount of carbon dioxide into atmosphere which is the root cause of green house effect and world's climatic changes. Since last decade Green composites are emerging as a realistic alternative to glass fibre composites in many applications such as automotive, construction, leisure, sporting industries because of lower cost and lower density. The ecological characteristics, biodegradability, low costs, safe fibre handling, non-abrasive nature, low energy consumption, high specific properties, low density and wide variety of fibre types are very important factors for the acceptance of Green composites in automobile and construction industry. Some other potential fields of Green composites are door and instrument panels, package trays, glove boxes, arm rest, seat backs. Natural fibres are recyclable and are environmental friendly due to less dependence on non-renewable energy/ material resources, lower pollutant emissions, lower greenhouse gas emissions, more energy recovery. The objective of this paper is to discuss and encourage the use of Green composites in various industrial applications. In this paper a study of Green composites on the basis of energy consumption and environmental aspects is done.

INTRODUCTION

The use of natural fibres as reinforcement in polymeric composites for technical applications has been a research subject of scientists during the last decade. There is a great interest in the application of natural fibres as substitutes for man-made synthetic fibres, motivated by potential advantages of weight saving, relative high strength and stiffness, lower raw material price, and ecological advantages of using green resources which are renewable and biodegradable. Products made of natural fibres offer environmental advantages; they require

less energy during manufacture and are relatively easy to recycle after the end of their useful life. In this paper we present a comparative study of eco-friendly natural fibre composites and man-made synthetic (Glass fibre) composites which encourages the use of natural fibres composites over synthetic composites. The objective of this paper is to discuss and encourage the use of natural fibre composites in various industrial applications. In this paper we are comparing the natural fibre composites and glass fibre composites on the basis of energy consumption and environmental aspects.

ENERGY SAVINGS

Energy consumption comparison:hemp vs. glass fibre composites

In Table below, a detailed comparison is shown for energy consumption between hemp based and glass fibre composites. The main reference in this regard is the work of Corbiere- Nicollier et al. 2001 based on life cycle assessment of biofibers replacing glass fibers in plastics.

Overall energy consumption schedule for Natural fibre Mat Thermoplastic & Glass fibre Mat Thermoplastic:

	Quantity(1metric ton)	NMT(65%ofibre)	MJ	GMT(30%ofibre)	MJ
1	Materials	Hemp Cultivation	1340	GlassFibreProduction	14500
		PP Production	35350	PP Production	70700
		Total	36690	Total	85200
2	Production	Composite	11200	Composite	11200
3	Incineration				
	PPIncineration	EnergyRequired	117	EnergyRequired	234
		EnergyReleased	-7630	EnergyReleased	-15260
	HempFibreIncineration			GlassFibreIncineration	
	EnergyRequired		1108	EnergyRequired 516	
	EnergyReleased		-10650		
	Net		17055	Net -14510	
4	Balance	Gross EnergyRequired	49115	Gross EnergyRequired	97150
		EnergyReleased	-18222	EnergyReleased	-15260
		Net energyrequired	30800	Netenergyrequired	81890

From above table, it is evident that natural fiber composites consume only 37% energy in their entire life cycle as compared to glass fiber composites. In other words for a same amount of product 60% savings is achieved. The low savings in terms of incineration can be attributed to high incineration value of PP compared to hemp fiber as shown in above table. The net saving of around 50 000 MJ by using 65% hemp fibers instead of 30% glass fibers in thermo plastic matrix not only saves non-renewable fossil fuels to a great extent but also helps in reducing CO₂ level in the atmosphere.

ENVIRONMENTALIMPACTCONSIDERATIONS

It has been already pointed out that the use of natural-organic fillers allows obtaining several environmental advantages in comparison to mineral-inorganic counterparts. The environmental impact,infact,can be improved mainly due to there duct ion in the use of

fossil-based resources (especially petroleum). A detailed paper has been written by Joshi et al. collecting and discussing some LCA assessment studies on composites filled with, respectively, natural-organic fillers (NFR) and glass fibers (GFR). Joshi then proposes a generalization of the results, identifying and presenting four interesting indicators of the superior relative environmental performance of NFR composites in comparison to GFR ones. These can be summarized as follows:

(A) Environmental impacts of natural fiber vs. glass fiber production: NF win because of energy consumption (solar energy vs. thermal energy from fossil fuels) and lower emissions (except for nitrates). Table A below shows the estimated life cycle non-renewable energy requirements for production of glass fiber and two natural fibres. As can be seen glass fiber production requires 5–10 times more non-renewable energy than natural fiber production. As a result, the pollutant emissions from glass fiber production are significantly higher than from natural fiber production. Columns 2 and 3 of Table B tabulate the environmental impacts from glass fiber production and china reed fibre production processes. Except for nitrate emissions associated with fertilizer use in china reed production, all other emissions are much lower for natural fibres. Increased nitrate emissions can lead to eutrophication of water bodies, which is a significant water quality problem in many areas. However, Corbiere et al. find that life cycle eutrophication impacts of NFR composites are lower than life cycle eutrophication effects of GFR composites, when they include contribution of atmospheric NOx emissions to eutrophication. These observations are likely to be valid across different natural fibers, since their production processes are very similar. Hence substitution of glass fibers by natural fibers of equal weight normally improves environmental performance of the component, with possible exception of local eutrophication effects.

Table A: Non renewable energy requirement for production of different fibres

Non renewable energy requirement (MJ/Kg)					
Glass fibre mat		Flax fibre mat		China breed fibre	
Raw material	1.7	Seed production	0.05	Cultivation	2.50
Mixture	1.0	fertilizers	1.0	Transport plant	0.40
Transport	1.6	Transport	0.9	Fibre extraction	0.08
Melting	21.5	Cultivation	2.0	Fibre grinding	0.40
Spinning	5.9	Fibre separation	2.7	Transport fibre	0.26
Mat production	23.0	Mat production	2.9		
TOTAL	54.7	TOTAL	9.55	TOTAL	3.64

Table B: Life cycle environmental impacts from production of glass fibre, epoxy resin, ABS and PP

Environmental	Glass Fibre	Impact	China Reed	Epoxy Resin	ABS Fibre	Polypropylene
Energy use (MJ/kg)	48.33		3.64	140.71	95.02	77.19
CO ₂ emissions (kg/kg)	2.04		.66	5.90	3.1	1.85
CO emissions (gm/kg)	.80		.44	2.2	3.8	.72
SO _x emissions (gm/kg)	8.79		1.23	19	10	12.94
NO _x emissions (gm/kg)	2.93		1.07	35	11	9.57
Particulate Matter (gm/kg)	1.04		.24	15	2.9	1.48
BOD to water (mg/kg)	1.75		.36	1200	33	33.94

COD to water(mg/kg)	18.8 1	2.27	51000	2200	178.92
Nitrates to water(mg/kg)	14	244811	71		18.78
Phosphates to water(mg/kg)	43.06233.6	220	120		3.39

- (B) Replacement of base polymer by higher polymer volume percentage of natural fibre: In order to obtain comparable mechanical properties, higher volume fractions of NF are used and this favours a lower use of oil-derived polymers. NFR components typically will have a higher fiber volume fraction compared to GFR components for equivalent strength and stiffness performance, because glass fibers have better mechanical properties than natural fibers. This higher fiber volume fraction reduces the volume and weight fraction of the base polymer matrix used in the composite. The life cycle energy use and emissions from the production of most base polymers used in composites are significantly higher than those associated with natural fiber production. For example, columns 4–6 in Table B show estimates of life cycle energy use and emissions from production of 1 kg of epoxy resin, ABS and PP extracted from APME eco-profiles. These can be compared to the life cycle emissions associated with 1 kg of china reed fiber production shown in column 3 and it is obvious that energy use and emissions associated with base polymer production are significantly higher than those associated with natural fiber production. For example, PP production requires about 20 times more energy than natural fiber production and correspondingly the emissions are also higher. These observations are valid across most natural fibers and base polymers. Hence substitution of base polymer by higher natural fiber fraction will improve the environmental performance of NFR composites compared to equivalent GFR composites.
- (C) Reduced emissions during service life of the product, due to lower weight: NFR composites have lower specific weights than GFR composites and this, in turn, reduces energy consumption both directly (e.g. in the case of composites used for automotive applications) and indirectly (reduction of emissions due to product transport and delivery). This higher volume fraction of lower density natural fibers in NFR composites also reduces the weight of the final component. Table C shows the weights of equivalent GFR and NFR components from the three studies. As can be seen NFR components result in 20–30% reduction in weight. Natural fiber composites are becoming popular in automotive applications because of this weight reduction. Lower weight components improve fuel efficiency and in turn significantly lower emissions during the use phase of the component life cycle.

Table C: Weight Reduction with natural fibre composites:

Component	Source study	Conventional composite materials	Weight (gm) of reference component	Weight (gm) of NFR materials	Weight (gm) of NFR component	Weight reduction (%)
Auto side panel	[7]	ABS	1125	Hemp-	820	27

				Epoxy		
Auto insulation panel	[5]	Glass Fiber- PP	3500	Hemp-PP	2600	26
Transport pallet	[4]	Glass Fiber-PP	15000	China reed- PP	11770	22

- (D) Carbon and Energy credits from natural fibres incineration: Differently from glass fibres, natural fibres can be conveniently incinerated at the end of product's service life, with a double advantage of energy recovery and no net additional CO₂ emission, since the CO₂ released during combustion is theoretically the same which was taken up by the plant from the atmosphere, during its growth. Hence incineration of NFR composites leads to positive carbon credits and lower global warming effect.

CONCLUSION

From the various studies we have found that natural fibre composites are environmentally more superior to glass fibre composites in most applications, except for higher nitrate and phosphate emissions which can lead to increased eutrophication in local water bodies. Full biodegradability of natural fibre composites can be obtained by replacing traditional polymers matrix with biodegradable ones which will further improved its environmental impacts. Research is also going on to enhance the mechanical properties and improve upon the other limitations of natural fibre composites.

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A Review on Application of 3D Printing in Biomedical Engineering

Sahil Shakya, Vineet Dubey

Department of Mechanical Engineering, Chandigarh University Unnao, Uttar Pradesh, India

ARTICLE INFO

Article History:

Published: 18 March 2026

Publication Issue :

Volume 13, Issue 7
March-April-2026

Page Number :

184-193

ABSTRACT

Three-dimensional (3D) printing, also called additive manufacturing (AM), has become an important technological breakthrough with increasing uses in the biomedical and healthcare fields. This technology makes physical objects directly from digital models by depositing materials layer by layer. This method allows for the creation of complex structures that are hard to make with traditional manufacturing techniques. In recent years, additive manufacturing has gained significant interest in the medical field because it can produce highly customized and patient-specific solutions. The combination of digital imaging, computer-aided design (CAD), and new biomaterials has led to the development of personalized implants, prosthetic devices, surgical planning models, and innovative drug delivery systems. One main benefit of 3D printing in healthcare is its ability to create anatomically accurate prosthetics and implants that enhance functionality, comfort, and patient health outcomes. Additionally, the technology shows promise in new fields like tissue engineering and bioprinting, where living cells and bio-compatible materials create tissue-like structures for regenerative medicine. Additive manufacturing also provides advantages such as rapid prototyping, design flexibility, less material waste, and cost-effective production. This makes it suitable for both advanced medical facilities and resource-limited settings. However, challenges still exist, including limitations in printable biomaterials, regulatory issues, and the need for specialized skills across various fields. This review discusses the principles of additive manufacturing, common biomaterials used, and its key biomedical applications, while also addressing the challenges and future possibilities of this technology in modern healthcare.

Keywords: 3D Printing, Biomedical Engineering, Bioprinting, Prosthetics, Implants.

INTRODUCTION

Three-dimensional (3D) printing is an advanced manufacturing technique through which digital designs can be converted into physical objects. This technology is commonly referred to as additive manufacturing (AM) or rapid prototyping, as it builds components by gradually adding material rather than removing it [1]. Additive manufacturing is based on layered manufacturing technology in which thin layers of material are stacked on top of one another to form the final product. Parts that have complex geometry can be easily manufactured by 3D printing using less material compared to traditional manufacturing methods [2].

Biomedical engineering is the application of engineering principles and techniques to design medical devices, equipment, and systems that assist healthcare professionals in the diagnosis, treatment, and monitoring of patients [3]. The medical industry has made extensive use of three-dimensional printing, which is ideal for creating free-shaped functional parts with detailed internal features, particularly in the creation of patient-specific biomedical devices [4]. Three-dimensional printing provides great flexibility in the production of biomedical devices. Unlike traditional manufacturing techniques, it enables the creation of complex geometries and detailed internal structures. This technology also allows control over material distribution and density, making it possible to manufacture lightweight biomedical devices with fewer components [2]. Biomedical devices and implants must match the patient's anatomical structure to function effectively. Producing such customised devices using traditional manufacturing techniques can be difficult and time-consuming. Furthermore, because these devices are often designed for patient-specific applications, each product must be individually designed and developed according to the needs of a particular patient [5]. Three-dimensional printing has become a widely used technology in the biomedical field due to its high precision and ability to produce structures with excellent geometrical accuracy. Moreover, this technology makes it possible to manufacture complex implants by utilising medical imaging data such as Magnetic Resonance Imaging (MRI) and Computed Tomography (CT), which has further enhanced the capabilities of 3D printing by enabling the development of accurate and customised biomedical implants [6,7].

Three-dimensional bioprinting is an important application of 3D printing technology that enables the fabrication of complex three-dimensional living tissues and artificial organs [8]. This technology typically uses biomaterials such as hydrogels, silicone-based materials, and protein solutions as printing materials. The primary objective of bioprinting research is to develop functional and transplantable human organs in the future [9].

Post-processing is essential in biomedical additive manufacturing. The layer-by-layer fabrication process can produce stair-stepped surface features that may negatively affect implant biocompatibility. As a result, careful surface finishing procedures are necessary to achieve the required surface quality [10]. Additionally, the production of medical devices such as implants must take place in sterile and controlled environments, and strict precautions should be followed to prevent contamination of the printing platform and other printing equipment [11].

Literature Review

Additive manufacturing has become an important technology in biomedical engineering due to its ability to produce complex and patient-specific medical devices. Gibson et al. [1] explained the fundamental principles of additive manufacturing and highlighted its potential for fabricating customized structures for medical and engineering applications. Bandyopadhyay et al. [11] further emphasized the importance of biomaterials in 3D printing, particularly for the development of biomedical implants and tissue engineering scaffolds.

The advancement of bioprinting has significantly expanded the applications of additive manufacturing in regenerative medicine. Murphy and Atala [16] discussed the potential of 3D bioprinting for fabricating biological tissues and organs using living cells and biomaterials. Similarly, Zhang et al. [8] reviewed the opportunities and challenges associated with bioprinting technologies, including issues related to material compatibility and long-term tissue functionality.

Several studies have demonstrated practical applications of 3D printing in medical treatments and surgical procedures. Saijo et al. [19] reported the use of custom-made artificial bones fabricated through 3D printing for mandibular reconstruction. Wang et al. [20] further investigated patient-specific titanium implants designed using rapid prototyping techniques to repair mandibular defects. In dental applications, Rezaie et al. [21] highlighted the role of 3D printing in producing dental prostheses such as crowns and bridges.

In addition, Hetherington [23] developed a 3D printed prosthetic hand controlled by electromyography (EMG) signals, demonstrating the potential of additive manufacturing in the development of assistive devices for individuals with limb loss. Mathew et al. [22] also discussed the use of 3D printing in pharmaceutical sciences, particularly for the development of personalized drug delivery systems. These studies collectively demonstrate the growing significance of 3D printing in biomedical engineering, particularly in areas such as prosthetics, implants, tissue engineering, dental applications, and drug delivery systems.

Stages of the 3D Printing Process

The 3D printing process typically involves several stages: **(a)3D Modelling**: creating a digital 3D model of the target object. **(b)File Conversion**: converting the model into a printer-compatible format such as STL. **(c)3D Slicer Software**: slicing the model into layers using specialised slicing software to generate G-code, which are the machine instructions that tell a 3D printer exactly how to move and deposit material. **(d)File Transfer**: transferring the G-code to the 3D printer. **(e)3D Printing**: Reads G-code line by line and executes the movement to fabricate the object layer by layer. **(f)Post-Processing**: - After the printing process, the support structure is removed, and post-processing operations such as painting, polishing, sanding, gap filling, etc. are performed.

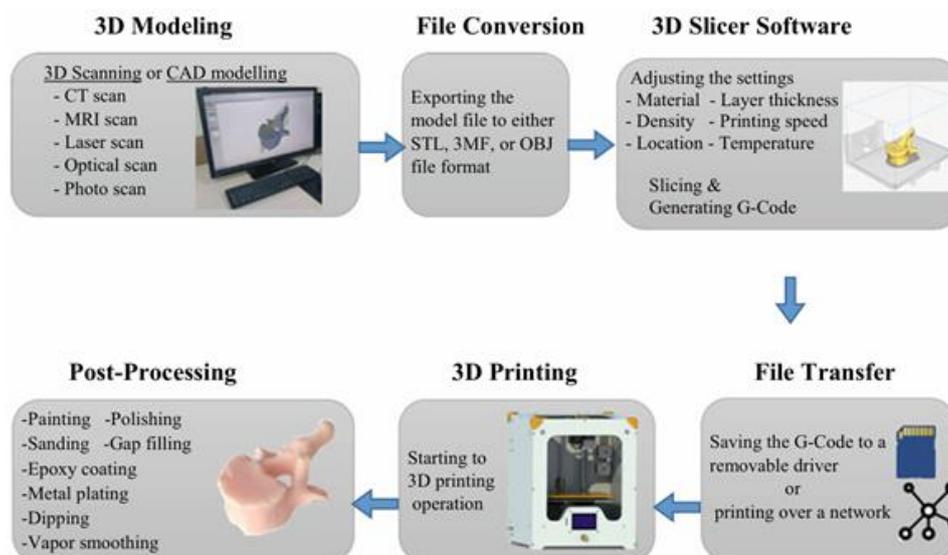


Fig.1 Stages of the manufacturing process using 3D printing technology [2]

Major 3D Printing Technologies in Biomedical Applications

4.1 Stereolithography (SLA): This is the most used technology of 3D printing in biomedical engineering because of its high precision, smooth surface finish, and ability to fabricate patient-specific biomedical devices. Stereolithography is an additive manufacturing process that uses ultraviolet (UV) light to cure and solidify liquid photopolymer resin layer by layer. It is widely used in biomedical fields for producing high-resolution anatomical models and dental components [12].

4.2 Fused Deposition Modeling (FDM): Fused Deposition Modeling is a 3D printing technique that works by extruding thermoplastic filaments through a heated nozzle to build objects layer by layer. In biomedical applications, it is commonly used for prototyping, surgical guides, and anatomical models [13].

4.3 Selective Laser Sintering (SLS): Selective Laser Sintering is a 3D printing technology that uses a laser to fuse powdered materials such as polymers or metals into solid structures. In biomedical applications, it is used to manufacture custom implants and porous scaffolds for bone growth [14].

4.4 PolyJet / Material Jetting. PolyJet or Material Jetting is a 3D printing technique that deposits tiny droplets of photopolymer materials and cures them using UV light to create precise objects. This technology is useful for producing multi-material biomedical models that mimic the properties of human tissues [15].

4.5. Bioprinting: Three-dimensional bioprinting is an advanced form of additive manufacturing that enables the printing of biocompatible materials, living cells, and supporting components to create complex three-dimensional functional biological tissues. This technology allows the layer-by-layer fabrication of living tissue structures that can mimic natural biological systems. Bioprinting has several biomedical applications, including tissue engineering, drug testing, disease modeling, regenerative medicine, and the development of transplantable organs [16]

Other than these commonly used technologies, several other additive manufacturing techniques are also utilized in biomedical engineering, including Selective Laser Melting (SLM), Electron Beam Melting (EBM), Digital Light Processing (DLP), Binder Jetting, Direct Ink Writing (DIW), Laser Engineered Net Shaping (LENS), and Continuous Liquid Interface Production (CLIP).

Current Applications in Medical Devices and Implants

The integration of additive manufacturing (3D printing) into biomedical engineering has significantly changed the way medical devices and implants are produced. Initially, it was used mainly for prototyping, this technology has now become an important manufacturing method for developing patient-specific medical solutions. Compared with traditional subtractive manufacturing techniques, 3D printing provides greater design flexibility, improved anatomical accuracy, and the capability to fabricate complex customized structures in a cost-effective manner [17].

5.1 Applications in Orthopedic Surgery and Implants

Rapid prototyping has been applied in orthopedic surgery to support the analysis and treatment of complex fractures. Potamianos et al. reported a case involving a patient with a shoulder injury consisting of fractures in both the clavicle and scapula that required surgical stabilization using plate and screw fixation [18]. Computed tomography (CT) data of the shoulder bones were processed through segmentation to generate a three-dimensional model, which was then fabricated using stereolithography (SLA). The physical model enabled detailed visualization of the fracture pattern, revealing a complete transverse fracture of the clavicle while the scapula remained partially attached. Such models help surgeons better understand bone structures and plan appropriate surgical procedures and implant placement [2,18].

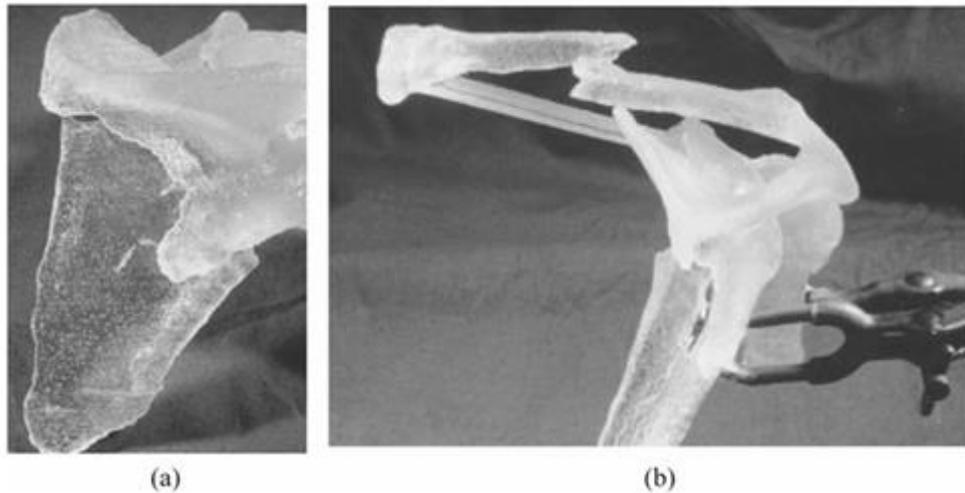


Fig.2 Three-dimensional printed model of the shoulder. Oblique posterior view (a) and medial view (b), which show the fracture [18].

5.2 Applications in Surgical Planning and Implants

3D printing technology has also been applied in maxillofacial surgery for the treatment of mandibular deformities. Saijo et al. reported the use of custom-made artificial bones fabricated through inkjet-based 3D printing for reconstruction of the lower jaw [19]. These patient-specific implants were designed to match the anatomical structure of the mandible and were surgically implanted into the affected region. Rapid prototyping techniques were also used to create plaster models that assisted surgeons in preoperative planning. The results showed good dimensional compatibility between the artificial bones and the patients' anatomy, with partial integration observed between the implant and host bone tissue and no major adverse reactions. In addition, the use of customized implants reduced surgical time by minimizing the need for intraoperative adjustments and fixation procedures [2,19].

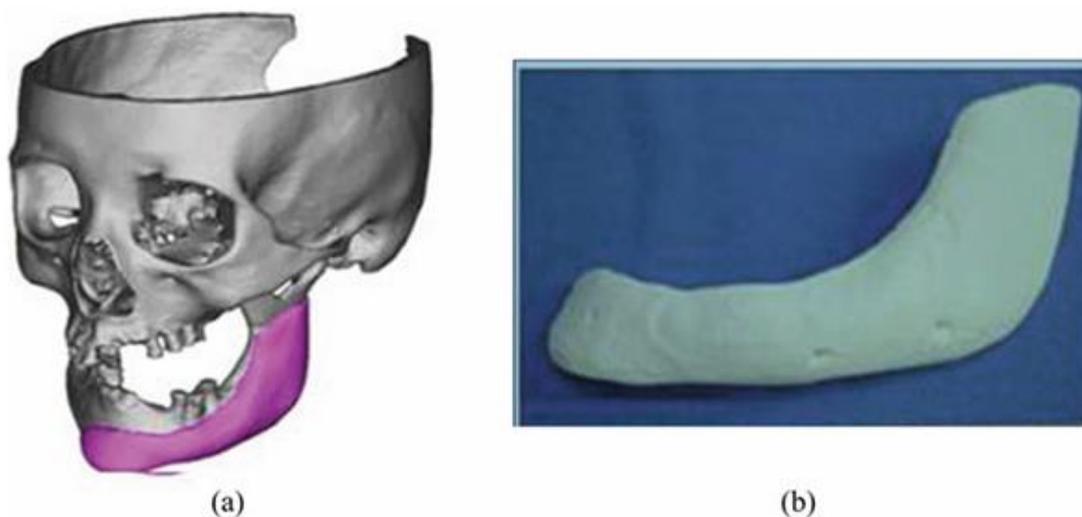


Fig. 3 Modeling and production of artificial mandibular bone. a The CAD model of the target area and b inkjet-printed custom-made artificial bone [19].

Rapid prototyping techniques are increasingly used in reconstructive surgery to create patient-specific implants for mandibular defects and fractures. Wang et al. reported a case involving facial asymmetry and structural

deformities following mandibular reduction surgery [20]. Using anatomical data of the patient, a customized titanium mesh implant was designed through CAD/CAM and fabricated using rapid prototyping to reconstruct the damaged region of the mandible, including the ramus. Postoperative results showed that the implant closely matched the original bone structure and helped restore facial symmetry. The study highlights the usefulness of 3D printing technologies in improving surgical accuracy and addressing complex mandibular reconstruction cases [2,20].

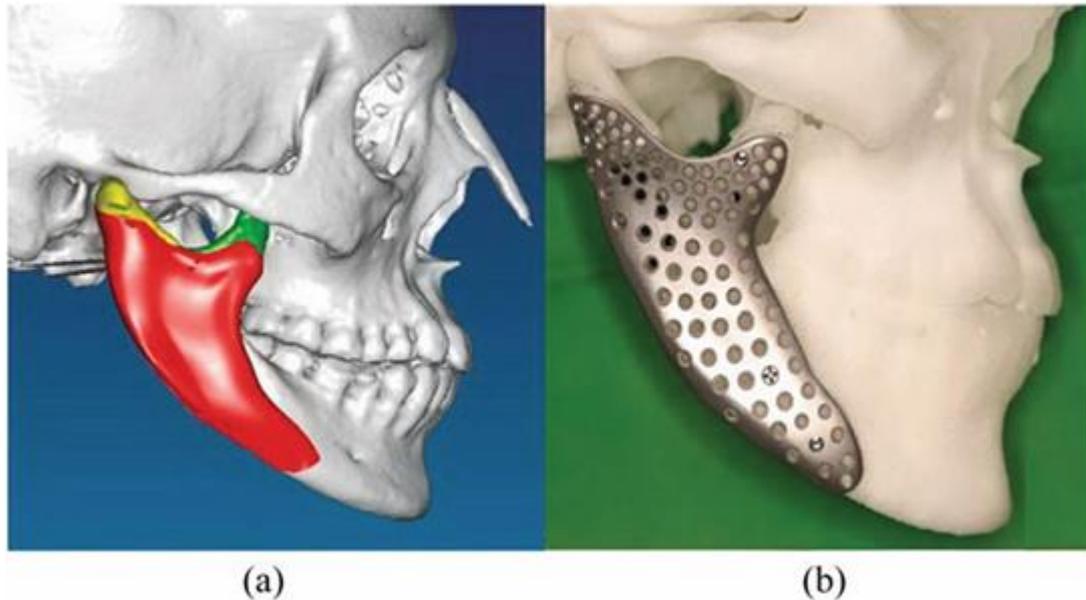


Fig.4 Reconstruction of bone defects by the custom-specific implant. a The CAD model of the craniofacial structure and implant. b Custom-made implant [20]

5.3 Dental Applications and Prosthetics

Three-dimensional printing has become an important technology in modern dentistry, particularly in the fabrication of dental prostheses and restorative devices. By using digital dental scans and computer-aided design (CAD), customized prosthetic components such as crowns, bridges, dentures, and orthodontic appliances can be produced with high accuracy and improved fit [21]. Compared with conventional manufacturing methods, 3D printing enables faster production, reduced material waste, and greater design flexibility. The technology also allows the development of patient-specific dental restorations that improve both functional performance and aesthetic outcomes. As a result, additive manufacturing is increasingly being adopted in dental laboratories and clinical practice for efficient and precise prosthetic fabrication [21].

5.4 Pharmaceutical and Drug Delivery Applications

Three-dimensional printing is increasingly being explored in pharmaceutical research for the development of personalized drug formulations and novel delivery systems. Unlike conventional manufacturing methods that produce standardized medicines, additive manufacturing allows dosage forms to be designed according to patient-specific requirements such as age, weight, and medical condition. This enables more accurate control over drug dosage and release characteristics [22].

3D printing also supports the development of advanced drug delivery systems with controlled release profiles. By adjusting the material composition and internal structure of printed formulations, it is possible to achieve delayed, sustained, or pulsatile drug release. In addition to oral dosage forms, the technology can be used to

fabricate drug-eluting implants and microneedle systems for localized therapy. Despite its advantages, the use of 3D printing in pharmaceutical manufacturing requires careful regulation to ensure product quality, safety, and consistency [22].

5.5 3D-Printed Prosthetic Limbs and Assistive Devices

Hetherington and colleagues developed a prosthetic limb using additive manufacturing technology [23]. The prosthetic hand was fabricated through 3D printing and operated using signals generated by forearm muscles. These signals were detected by electromyography (EMG) sensors, which allowed the hand to move in response to muscle activation. Such prosthetic devices produced through modern manufacturing techniques are generally lightweight, cost-effective, customizable, and easier to replace compared with conventionally manufactured prosthetics [2,23].



Fig.5 Three-dimensional printed EMG-driven prosthesis developed and built by SenseTech [23].

Future Directions and Emerging Technologies

3D printing, also known as additive manufacturing (AM), is constantly changing and will completely change biomedical engineering and healthcare delivery in the coming decade. The field is moving beyond making static, patient-specific models and implants and is now working with advanced materials science, artificial intelligence (AI), and systems engineering to create medical solutions that can adapt, learn, and heal themselves [24].

6.1 4D Printing and Smart Biomaterials

The shift from 3D to 4D printing is a big change in the way things are made. It adds a time-dependent, dynamic dimension to printed objects. 4D-printed things are made from smart materials that can change their shape, properties, or how they work when they are exposed to certain external factors, like temperature, moisture, pH, or biological signals, which can affect the printed object after it has been made [24]. This ability opens new possibilities for adaptive therapies and less invasive medical procedures. In the future, there will be self-expanding hydrogel stents for heart surgery, smart bone implants that change their load-bearing properties

to help healing, and biodegradable programmable sutures (smart surgical stitches that can change their behaviour or gradually dissolve in the body after fulfilling their function) [24].

6.2 Responsive Tissue Engineering and Organ-on-a-Chip

The integration of bioprinting, smart materials, and microfluidics is accelerating progress in regenerative medicine and advancing in vitro models. The future of tissue engineering is likely to rely on dynamic scaffold systems composed of stimuli-responsive materials that can modify their structure and porosity or mechanical stiffness to direct various phases of tissue regeneration. A major research focus in bioprinting is the development of functional vascular networks within printed tissues. This is achieved by using sacrificial materials or directly printing endothelial cells to create perfusable channels that support nutrient and oxygen transport in larger tissue constructs [25].

Also, combining 3D bioprinting with microfluidic chips is making advanced organ-on-a-chip (OoC) platforms. These systems create a dynamic, physiologically relevant microenvironment for bioprinted tissue models, which lets researchers study disease mechanisms, drug responses, and interactions between organs with an accuracy never before seen. This synergy is especially useful for making drugs and personalized medicine because it provides human-relevant models that can reduce reliance on animal testing [25].

6.3 Artificial Intelligence and Machine Learning Integration

The integration of artificial intelligence (AI) and machine learning (ML) is revolutionizing every stage of the biomedical 3D printing workflow, from design to post-processing [26].

AI-Enhanced Design and Personalization: AI algorithms, particularly deep learning models, can automatically process medical imaging data (CT, MRI) to generate optimized, patient-specific 3D models for implants, prosthetics, and anatomical models. This automation reduces the need for time-consuming manual segmentation and enables generative design approaches that create optimized lattice structures for improved strength and stress distribution [26]. In bioprinting, machine learning can also predict suitable bioink formulations by evaluating how molecular variations influence printability and tissue viability [26].

Intelligent Process Control and Quality Assurance: Machine learning and reinforcement learning techniques allow for real-time monitoring and dynamic adjustment of printing parameters (e.g., temperature, speed) to ensure the best quality. AI-powered computer vision systems can detect problems like warping or misaligned layers while printing, allowing for immediate corrections and significantly reducing material waste and production errors [26].

Predictive Analytics and Simulation: AI can simulate how a 3D-printed implant performs under real-life conditions before it is made. This helps doctors choose the right design [26]. Additionally, AI-driven predictive models are important for forecasting demand in healthcare supply chains. They enable efficient on-demand and point-of-care manufacturing of medical devices [26].

Conclusion

Three-dimensional (3D) printing has become a game-changing technology in biomedical engineering. It allows for the creation of highly customized medical devices and treatment solutions. By using digital design and specific patient data, additive manufacturing helps in producing implants, prosthetics, and anatomical models with better precision and functionality. This technology shows great promise in areas like surgical planning and implants, drug delivery, tissue engineering, prosthetic limbs and assistive devices, dental, maxillofacial and

orthopedic applications. The ability to create complex structures and personalized medical devices has made treatments more efficient and improved patient health outcomes.

Despite these benefits, some challenges still exist. There is a limited supply of suitable biomaterials, high equipment costs, and regulatory issues regarding clinical use. Ongoing improvements in biomaterials, printing methods, and collaboration across fields are expected to tackle these challenges. As research and technology continue to advance, 3D printing is likely to become more important in modern healthcare. It can help make medical solutions more efficient, accessible, and focused on patients.

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An Empirical Study of Barriers to Green Manufacturing Practices in Indian Small-Scale Industries

Shivakar Prasad¹, Rakesh Kumar¹, Satish Namdev²

¹Department of Mechanical Engineering, Manipal University Jaipur-303007, Rajasthan India

²Automobile Engineering, Government Polytechnic Aadampur Tarabganj Gonda-271401, Uttar Pradesh India

ARTICLE INFO

Article History:

Published: 18 March 2026

Publication Issue :

Volume 13, Issue 7
March-April-2026

Page Number :

194-198

ABSTRACT

Green manufacturing has emerged as an essential strategy for achieving sustainable industrial development while reducing environmental impacts. It focuses on minimizing waste, improving energy efficiency, and reducing harmful emissions during manufacturing processes. Despite the growing importance of sustainable production systems, the adoption of green manufacturing practices in Indian small-scale industries remains limited. This research paper aims to identify and analyze the key barriers affecting the adoption of green manufacturing practices in Indian small-scale industries. An empirical research approach was used by collecting primary data through a structured questionnaire from managers and engineers working in small manufacturing units. The findings reveal that financial constraints, lack of awareness, technological limitations, insufficient government support, and low consumer demand are the most significant barriers to green manufacturing adoption. The study suggests policy measures, training programs, and financial incentives to encourage sustainable manufacturing practices in Indian small industries.

Keywords: Green manufacturing, sustainable manufacturing, SMEs, environmental sustainability, barriers, Indian industries.

INTRODUCTION

Industrial growth has played a vital role in the economic development of many countries, including India. However, rapid industrialization has also resulted in environmental problems such as pollution, excessive energy consumption, and resource depletion. To address these issues, industries worldwide are increasingly adopting green manufacturing practices, which aim to minimize environmental impacts while maintaining production efficiency.

Green manufacturing involves the use of environmentally friendly materials, energy-efficient technologies, waste reduction strategies, and sustainable production systems. These practices help industries reduce emissions, conserve natural resources, and promote long-term sustainability.

In India, small-scale industries (SSIs) or micro, small, and medium enterprises (MSMEs) contribute significantly to employment generation and economic growth. However, the implementation of green manufacturing practices in these industries is still limited due to several challenges.

Research indicates that small and medium enterprises in developing countries struggle to adopt green manufacturing practices because of limited financial resources, lack of technical knowledge, and weak policy support.

Therefore, identifying the barriers to green manufacturing adoption in small-scale industries is essential for developing effective strategies to promote sustainable industrial growth in India.

LITERATURE REVIEW

Green manufacturing has gained increasing attention in recent years as industries attempt to reduce environmental impacts and improve sustainability. It involves efficient use of resources, reduction of hazardous substances, and minimizing waste during production processes.

Several studies have examined the barriers to green manufacturing adoption in small and medium enterprises. Financial constraints are often considered the most significant barrier because green technologies require high initial investment costs.

Another major barrier is the lack of awareness and technical knowledge about sustainable manufacturing technologies. Many small industries lack access to environmental information and training programs necessary for implementing green manufacturing systems.

Technological limitations and lack of skilled workforce also hinder the adoption of green manufacturing practices in SMEs. Additionally, weak government incentives and low consumer demand for eco-friendly products further discourage industries from adopting green technologies.

Previous research has identified several categories of barriers, including financial, organizational, technological, regulatory, and market barriers affecting the implementation of green manufacturing practices.

OBJECTIVES OF THE STUDY

The main objectives of this research are:

1. To identify the major barriers affecting green manufacturing practices in Indian small-scale industries.
2. To analyze the impact of these barriers on the adoption of sustainable manufacturing practices.
3. To propose strategies for overcoming these barriers and promoting green manufacturing adoption.

RESEARCH METHODOLOGY

➤ Research Design

This study adopts an **empirical research design** based on survey data collected from small-scale manufacturing industries.

➤ Data Collection

Two types of data were used:

Primary Data:

Primary data were collected through a structured questionnaire distributed among managers, engineers, and supervisors working in small manufacturing industries.

Secondary Data:

Secondary data were collected from journals, books, conference papers, and government reports related to green manufacturing and sustainability.

➤ **Sample Size**

A total of 100 respondents from small manufacturing units were selected using random sampling.

Data Analysis Techniques

The collected data were analyzed using:

- Percentage analysis
- Mean ranking method
- Descriptive statistical analysis

CONCEPTUAL FRAMEWORK OF BARRIERS TO GREEN MANUFACTURING

Below is a conceptual diagram showing the major barriers affecting green manufacturing adoption in small-scale industries.

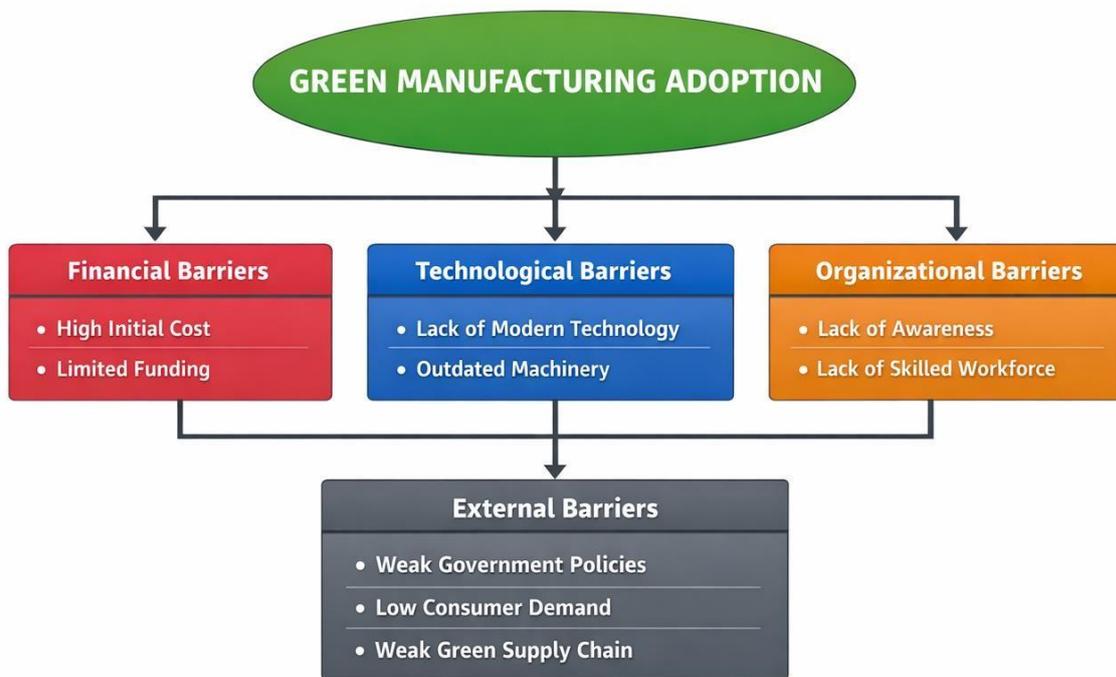


Figure: Conceptual Framework of Barriers to Green Manufacturing Adoption

MAJOR BARRIERS TO GREEN MANUFACTURING IN SMALL-SCALE INDUSTRIES

Based on literature review and survey analysis, the following barriers were identified.

Financial Barriers

Small-scale industries often lack sufficient financial resources to invest in green technologies. High initial investment costs discourage many firms from adopting sustainable production methods.

Lack of Awareness

Many industry owners and managers are not fully aware of green manufacturing technologies and their long-term environmental and economic benefits.

Technological Limitations

Small industries frequently operate with outdated equipment and lack access to modern eco-friendly manufacturing technologies.

Lack of Skilled Work force

Implementing green manufacturing practices requires trained personnel capable of operating sustainable technologies and environmental management systems.

Weak Government Support

Insufficient government incentives, complex regulatory frameworks, and lack of financial support programs reduce the motivation of small industries to adopt green manufacturing practices.

Market Barriers

Low consumer demand for environmentally friendly products reduces the economic incentives for adopting green technologies.

Supply Chain Limitations

Weak green supply chains and lack of environmentally responsible suppliers hinder sustainable manufacturing adoption.

RESULTS AND DISCUSSION

The empirical analysis indicates that financial constraints are the most significant barrier to green manufacturing adoption in small-scale industries. Small enterprises often operate with limited capital and cannot afford expensive eco-friendly technologies.

The second most important barrier identified is lack of awareness about sustainable manufacturing practices. Many industry managers lack adequate knowledge regarding environmental benefits and technological solutions available for green production.

Technological barriers and lack of skilled workforce also significantly affect the implementation of green manufacturing systems.

Additionally, limited government incentives and low consumer demand for green products further reduce the motivation for industries to adopt environmentally friendly practices.

Overall, the results indicate that both internal organizational factors and external environmental factors influence the adoption of green manufacturing practices in Indian small-scale industries.

RECOMMENDATIONS

Based on the findings of the study, the following recommendations are proposed:

1. Government should provide financial incentives and subsidies for adopting green technologies.
2. Training programs and awareness campaigns should be conducted to educate industry professionals about sustainable manufacturing.
3. Industries should invest in research and development of eco-friendly technologies.
4. Collaboration between government agencies, research institutions, and industries should be encouraged.
5. Development of green supply chain networks should be promoted.

CONCLUSION

Green manufacturing is essential for achieving sustainable industrial development and reducing environmental pollution. However, the adoption of green manufacturing practices in Indian small-scale industries remains limited due to several barriers such as financial constraints, lack of awareness, technological limitations, and insufficient policy support.

This study identified and analyzed the major barriers affecting the implementation of green manufacturing practices in Indian small-scale industries. The findings highlight the need for coordinated efforts by policymakers, industry managers, and researchers to overcome these challenges.

Encouraging green manufacturing adoption will not only improve environmental sustainability but also enhance the competitiveness and long-term growth of Indian small-scale industries.

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Hydrophobic and Superhydrophobic Coatings for Mitigating Dust Accumulation in Solar Photovoltaic Panels : A Literature Review

Shreyas Prasad¹, Dinesh Singh², Rajesh Kumar Sharma²

¹Department of Mechanical Engineering, FoET, DSMNRU, Lucknow, Uttar Pradesh, India

²Assistant Professor, Department of Mechanical Engineering, FoET, DSMNRU, Lucknow, Uttar Pradesh, India

ARTICLE INFO

Article History:

Published: 18 March 2026

Publication Issue :

Volume 13, Issue 7
March-April-2026

Page Number :

199-203

ABSTRACT

Photovoltaic (PV) panels convert sunlight into electricity through solar cells made from semiconducting materials like silicon, by exciting electrons and creating an electric field that generates a direct current (DC) which is then converted to alternating current (AC) by using an inverter making it usable in residential and solar farms for green energy production with types including monocrystalline, polycrystalline and thin film panels. Dust accumulation on photovoltaic (PV) panels significantly reduces solar energy conversion efficiency, particularly in arid and semi-arid regions. Soiling losses can reach 20-40% annually depending on environmental conditions. Hydrophobic and super hydrophobic coatings have emerged as passive anti-soiling solutions that reduce dust adhesion and enhance self-cleaning through rainfall or dew formation. This literature review critically examines recent studies (2023-2026) on hydrophobic nanocomposite coatings, hybrid SiO₂/TiO₂ multifunctional systems, durability performance, and climate-dependent effectiveness. The review identifies key performance metrics, degradation mechanisms, and research gaps relevant to large-scale deployment. Findings indicate that nanostructured superhydrophobic and hybrid coatings provide the most promising balance between transparency, durability, and efficiency recovery. However, long term field validation and economic feasibility remain critical challenges.

Keywords: Solar photovoltaic, dust accumulation, hydrophobic coating, super hydrophobic surface, antisoiling, self-cleaning, nanocomposite coatings.

INTRODUCTION

Solar photovoltaic technology is one of the fastest-growing renewable energy sources worldwide. However, environmental dust deposition on panel surfaces remains a major operational challenge. The glass cover of PV modules must maintain high optical transmittance to ensure maximum solar irradiance reaches the solar cells.

Dust deposition leads to:

- Reduction in light transmittance
- Increase in reflectance losses
- Partial shading and mismatch losses
- Elevated operating temperature
- Decrease in power output

In regions such as deserts and industrial zones, efficiency losses due to soiling can exceed 30%. Traditional cleaning methods (manual washing, robotic cleaning) require water, labour and maintenance costs.

Hydrophobic coatings provide a passive solution by reducing surface energy and minimizing particle adhesion. This review focuses on recent advancements and evaluates their feasibility for real-world PV systems.

Mechanism of Dust Adhesion and Hydrophobic Cleaning

2.1 Dust Adhesion Mechanisms

Dust particles adhere to PV surfaces due to:

1. Van der Waals forces
2. Electrostatic forces
3. Capillary forces (humidity-dependant)
4. Surface roughness and mechanical interlocking

The total adhesion force determines the difficulty of particle removal

Hydrophobicity is measured using water contact angle (θ):

- Hydrophilic: $\theta < 90^\circ$
- Hydrophobic: $\theta > 90^\circ$
- Superhydrophobic: $\theta > 150^\circ$

Superhydrophobic surfaces reduce contact area between water droplets and the surfaces, allowing droplets to roll off and carry dust particles.

The governing equation for contact angle is Young's equation:

$$\gamma(SV) = \gamma(SL) + \gamma(LV) * \cos(\theta)$$

Here

- $\gamma(SV)$: Interfacial tension between Solid and Vapour
- $\gamma(SL)$: Interfacial tension between Solid and Liquid
- $\gamma(LV)$: Interfacial tension between Liquid and Vapour
- θ : Contact angle between liquid and solid

Reducing surface energy $\gamma(SL)$ increases θ and improves self-cleaning performance.

Review of Recent Research (2023-2026)

3.1 Nanocomposite Superhydrophobic Coatings

Recent 2025 studies on PDMS based nano-composite coatings showed:

- Contact angle > 150°
- Sliding angle < 10°
- 8-15% improvement in energy yield
- Reduced temperature rise by 2-4°C

Nanostructured surfaces trap air pockets (Cassie-Baxter state), reducing effective dust adhesion.

Advantages:

- High self-cleaning efficiency
- Good transparency (>90%)

Limitations:

- Abrasion sensitivity
- Gradual loss of hydrophobicity under UV exposure

3.2 Hybrid SiO₂/TiO₂ Coatings

Hybrid coatings combine hydrophobic properties with photo catalytic activity.

Reported results (2025 studies):

- Optical transmittance >92%
- Enhanced UV resistance
- Improved mechanical hardness
- Organic contamination degradation

TiO₂ contributes photo catalytic cleaning while SiO₂ improves structural integrity.

This multifunctional approach is considered highly promising for long term applications.

3.3 Micron-Smooth Hydrophobic Coatings for Desert Regions

A 2024 durability focused study demonstrated that:

- 30% reduction in dust composition
- Retention of hydrophobicity after 500 abrasion cycles
- Minimal loss in transparency

Mechanical durability is critical for desert solar farms exposed to sandstorms.

3.4 Climate Dependant Performance

Research indicates hydrophobic coatings are most effective in:

- Regions with periodic rainfall
- Areas with dew formation

In extremely dry climates, additional technologies (like vibration, electrostatic cleaning) maybe required.

Performance Evaluation Metrics of Coatings

Most studies evaluated

Water Contact Angle (WCA)

Sliding Angle

Optical Transmittance

Soiling ratio

Maximum Power Output (P_{max})

Short circuit current (I_{sc})

for the study of performance and efficiency of photovoltaic panels before and after the application of Hydrophobic and Superhydrophobic coatings.

Effective coatings maintained:

WCA > 150°

Transmittance > 90%

Efficiency recovery > 85% after cleaning

Durability and Degradation Mechanism

Major degradation mechanisms include:

- UV induced polymer degradation
- Thermal cycling stress
- Sand abrasion damage
- Loss of nano surface structure texture

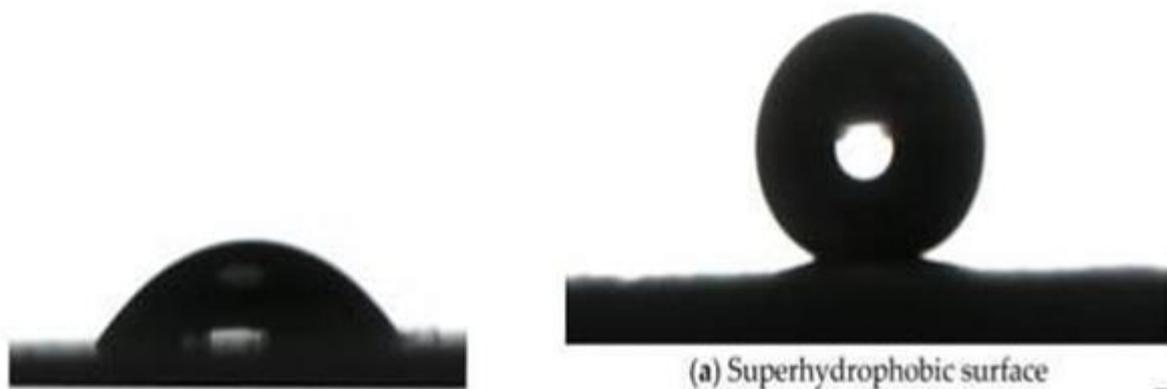
NOTE: Most coatings show noticeable performance reduction within 1-3 years under harsh conditions due to which research is now focussing on:

- Hard inorganic coatings
- Self healing materials
- Protective multilayer structures

Comparative Analysis

Coating Type	Hydrophobicity	Durability	Transparency	Suitability
Simple hydrophobic	Moderate	Moderate	High	Mild climates
Superhydrophobic nanocomposite	Very high	Moderate	High	Rainfall regions
Hybrid SiO ₂ /TiO ₂	High	High	Very high	Variable climates

Hybrid coatings appear most balanced for long-term use.



Research Gaps

- Lack of long term (5-10 year) field data
- Limited economic feasibility analysis
- Need for standardised dust testing methods
- Optimization for different climatic zones

Conclusion

Hydrophobic and superhydrophobic coatings significantly reduce dust induced efficiency losses in PV systems. Among recent technologies, nanocomposite superhydrophobic coatings and hybrid SiO₂/TiO₂ systems show the highest potential for maintaining optical transparency and improving energy yield. However, long term durability and cost-effective scalability remain major challenges. Further research should focus on multifunctional, abrasion-resistant, and climate-optimized coating solutions for sustainable solar energy systems.

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Artificial Intelligence in Supply Chain and Logistics: Emerging Applications and Future Challenges

Utkarsh Singh¹, A. K. Srivastava²

¹BBA 2nd Year SMS, Lucknow, Uttar Pradesh, India

²SIEF, Lucknow, Uttar Pradesh, India

ARTICLE INFO

Article History:

Published: 18 March 2026

Publication Issue :

Volume 13, Issue 7
March-April-2026

Page Number :

204-211

ABSTRACT

Artificial Intelligence (AI) has brought a major change in the field of logistics and supply chain management (SCM). As global supply networks get more complicated, companies are using AI-based solutions to make their operations more efficient, manage inventory better, predict demand more accurately, and lower transportation costs. Technologies like machine learning, predictive analytics, robotics, and the Internet of Things (IoT) help make decisions in real time and automate tasks in the supply chain. This paper looks at how AI is used in logistics and supply chain management, discusses its advantages and challenges, and suggests where future research could go. The study finds that using AI can greatly improve visibility, strength, and ability to react quickly in the age of digital change. **Keyword:** Artificial Intelligence (AI), supply chain management (SCM), Internet of Things (IoT)

INTRODUCTION

Artificial Intelligence (AI) is changing how supply chains work today by making them more efficient, accurate, and better at making decisions. Older supply chains depend a lot on people doing things by hand and using past data, which can cause problems like wasted time and delays. AI tools like machine learning, predictive analytics, robots, and smart automation help companies improve their logistics, guess what customers will want, manage their stock better, and work more smoothly with their suppliers.

AI helps supply chains look at a lot of real-time data and find patterns to know what will happen next. This lets companies save money, make customers happier, and make their supply chains more reliable. In the last few years, using AI together with other digital tools like the Internet of Things (IoT), blockchain, and cloud computing has made supply chains even stronger. Fig.1 shows AI based Vs Traditional supply chain Performance.

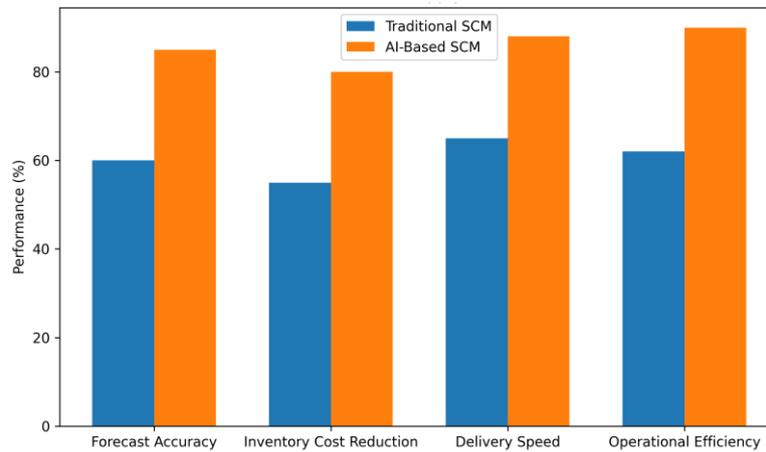


Fig. 1 : AI based Vs Traditional supply chain Performance

Literature Review

Supply Chain Management (SCM) has become a key part of modern business operations due to increased globalization, technological progress, and the need for sustainable and resilient logistics systems. In recent years, researchers have focused on improving supply chain efficiency, sustainability, risk management, and digital transformation.

2.1 Supply Chain Sustainability

Sustainability has become a major focus in supply chain research because of environmental concerns and new regulations. A. S. Abir et al. [1] and others created a multi-objective optimization model for sustainable closed-loop supply chain networks. Their study focused on reducing environmental impact while keeping economic efficiency. Similarly, D. Ivanov and A. Dolgui [2] introduced the idea of supply chain viability and talked about how interconnected supply networks must adjust to disruptions like global pandemics. Their research showed the importance of having flexible and adaptive supply chains. M. Christopher et al. [3] studied supply chain resilience during the COVID-19 pandemic and concluded that organizations need to redesign their supply chains to be flexible and able to manage risk in uncertain situations. In 2021, C.-T. Chiang et al. [4] and others looked at IT-based supply chain management systems and their role in achieving sustainability. Their study showed that digital tools like enterprise resource planning (ERP) systems improve transparency and coordination in supply chain operations. Sustainable supply chain management (SSCM) includes environmental, economic, and social factors in supply chain operations. M. Huda and M. Rahman [5] studied sustainable practices in manufacturing and found that using green procurement and eco-friendly logistics significantly reduces environmental impact. Similarly, M. Adamu and Y. Ahmed [6] developed sustainable supply chain frameworks for construction industries. Their research showed that using sustainable materials and reducing waste improves supply chain efficiency. A. Baysal [7] looked at engineering management in sustainable supply chains and concluded that organizations must use environmentally friendly production methods to stay competitive in global markets.

2.2 Digital Transformation in Supply Chains

Digital technologies like artificial intelligence, blockchain, and the Internet of Things (IoT) are changing supply chain management. R. Koundal and S. Sharma [8] studied supply chain optimization using data analytics and IoT. Their research showed that real-time data monitoring improves visibility and operational efficiency in supply chains. Similarly, M. Sanjay and B. Yogesha [9] looked at logistics performance and supply chain

integration in global markets. Their study found that integrated digital platforms help supply chain partners work together better. R. Kumar and P. Singh [10] looked at supply chain resilience through digital transformation and concluded that digital technologies help organizations respond quickly to disruptions. K. Pickering and J. Singh [11] emphasized the role of sustainable supply chains in improving environmental performance. Their study showed that including green practices in supply chains is important.

2.3 Artificial Intelligence and Smart Supply Chains

Artificial intelligence is being used more to improve decision-making in supply chains. M. Ibrahim et al. [12] developed hybrid supply chain optimization models using AI techniques. Their study showed that AI-based models improve forecasting and inventory management. Similarly, M. R. Hasan et al. [13] and others studied sustainable supply chains in the context of Industry 5.0. Their research showed that advanced digital technologies help create intelligent and human-focused supply chains. X. Li et al. [14] looked at circular economy supply chains and emphasized the importance of recycling, reuse, and resource efficiency in sustainable production. N. Saba et al. [15] examined sustainable supply chain systems for eco-friendly manufacturing. Their findings showed that using renewable resources and green technologies greatly reduces environmental impact.

2.4 Supply Chain Resilience and Risk Management

Supply chain disruptions caused by global events have made resilience more important. S. A. H. Shekarabi [16] and others did a critical review on supply chain resilience and risk management strategies. Their research showed the importance of using technologies like blockchain and digital monitoring systems. Similarly, Z. Ma [17] studied the design and development of supply chain management systems and concluded that advanced information systems improve coordination and operational performance. R. Aghaei et al. [18] looked at the potential of large language models in supply chain management. Their study showed that AI-driven analytics can help with planning and decision-making. H. Chen et al. [19] focused on sustainable manufacturing supply chains and digital technologies. Their study showed that digitalization improves efficiency, transparency, and sustainability in supply chain operations. Similarly, V. Patel and R. Singh [20] analyzed green supply chain practices in the automotive industry. Their research showed that using eco-friendly logistics lowers carbon emissions and operational costs.

2.5 Future Trends in Supply Chain Management

Recent research shows that digital technologies and sustainability are becoming more important in supply chain systems. M. S. Sharifi and A. Naimzad [21] did a systematic review on supply chain risk management and emphasized the importance of proactive risk assessment. Similarly, M.-K. Kieu et al. [22] explored new trends in supply chain integration and identified digital transformation, sustainability, and resilience as major areas for future research. P. Sharma and N. Gupta [23] studied advanced digital supply chain management systems for sustainable manufacturing. Their research showed that AI and big data analytics help improve supply chain performance. J. Lee and S. Park [24] looked at digital transformation in supply chain management using blockchain and AI technologies. Their study concluded that these help with transparency, traceability, and efficiency.

Overall, the literature shows that supply chain management has evolved a lot due to digital transformation, sustainability needs, and global disruptions. Fig. 2 shows Cloud-Based AI Framework for End-to-End Supply Chain.

Researchers have stressed the importance of using advanced technologies like AI, blockchain, and IoT to improve supply chain efficiency and resilience. Furthermore, sustainable supply chain management practices are becoming more common to reduce environmental impact and improve resource use. Even with these advances, challenges like supply chain disruptions, data integration problems, and difficulties in adopting new technologies still exist. Future research should focus on developing smart, sustainable, and resilient supply chain systems that can handle rapid changes in the global environment. Fig.3 shows Impact of AI adoption on supply chain efficiency.

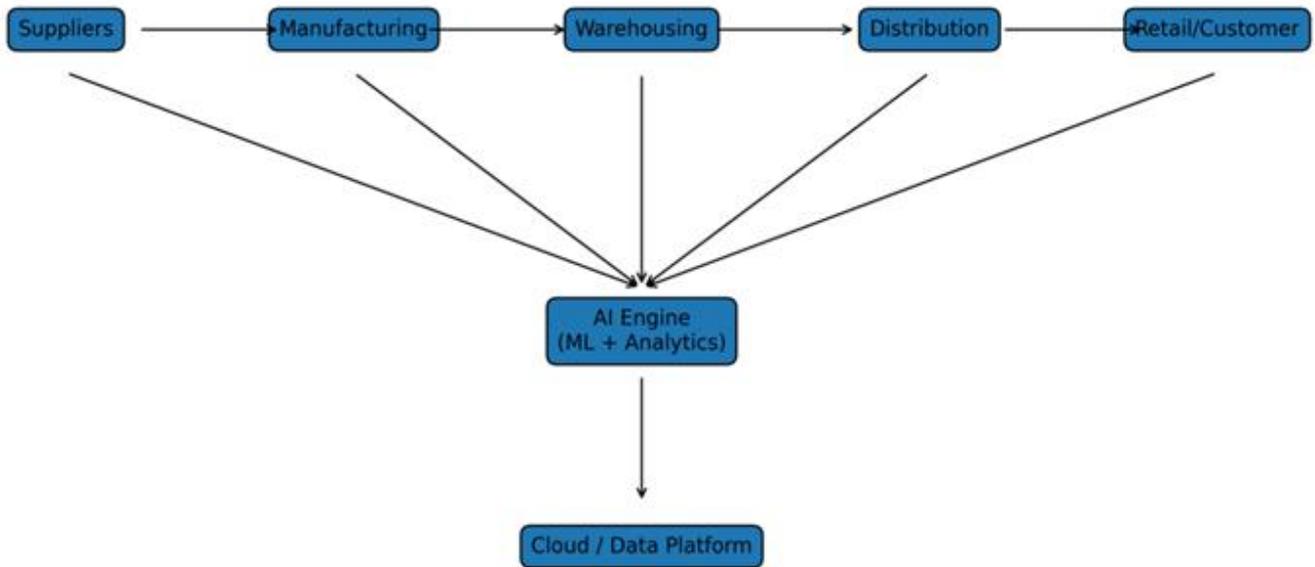


Fig. 2 : Cloud-Based AI Framework for End-to-End Supply Chain

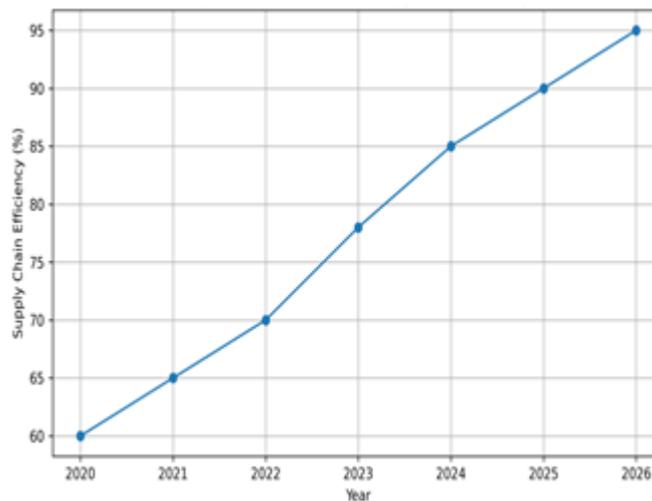


Fig.3 : Impact of AI adoption on supply chain efficiency

The Role of AI in Supply Chain Management

Artificial intelligence helps with many parts of supply chain management.

3.1 Demand Forecasting

One of the main uses of AI in supply chains is predicting how much product will be needed. AI uses machine learning to look at past sales, trends in the market, weather, and how customers act to make better predictions.

Benefits include:

- More accurate predictions of what customers will want
- Lower costs for storing extra products
- Better planning for making products

3.2 Inventory Management

AI helps manage how much stock is kept by predicting changes in demand and checking how much is in stock. Smart systems can change stock levels automatically to avoid having too little or too much. Benefits include: • Less money spent on storing inventory • More efficient warehouses • Fewer times products run out

3.3 Logistics and Transportation Optimization

AI uses data about routes, traffic, fuel prices, and delivery times to improve how goods are transported. This helps companies spend less on moving things and deliver faster. Applications include:

- Finding the best routes for delivery
- Using self-driving delivery vehicles
- Using robots in warehouses

3.4 Supplier Selection and Procurement

AI helps choose the best suppliers by looking at how well they perform, their prices, how fast they deliver, and possible risks. Benefits include:

- Better way to evaluate suppliers
- Fewer risks when buying from suppliers
- Faster decisions when choosing suppliers

3.5 Supply Chain Risk Management:

AI helps spot potential problems like natural disasters, pandemics, or political changes that might stop the supply chain. It suggests ways to avoid or handle these issues. Examples include: • Predicting if a supplier might stop working • Watching for changes in politics that might affect the supply chain • Estimating delays in shipping

AI Technologies Used in Supply Chain

Many different AI tools are used to make supply chains better. Fig.4 shows Architecture of AI-Based Supply Chain Analytics System.

Machine Learning : These systems use data to find patterns and make better choices.

Natural Language Processing (NLP): NLP helps with communication with suppliers and customers through chatbots and other systems.

Robotics and Automation : Robots are used to move, sort, and pack items in warehouses.

Computer Vision: These systems check product quality and track inventory in warehouses.

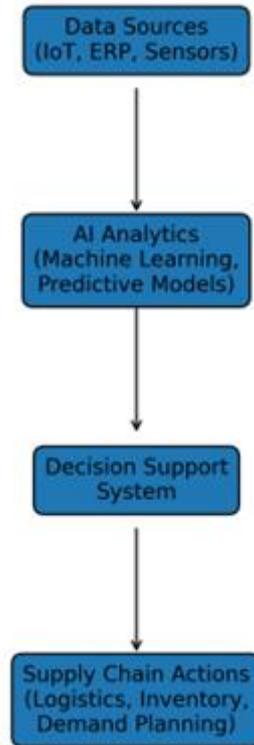


Fig.4 Architecture of AI-Based Supply Chain Analytics System

Benefits of AI in Supply Chain Management :

Using AI brings many advantages:

- More accurate predictions of what customers will buy
- Lower costs for running the supply chain
- Clearer view of the whole supply chain
- Faster decisions
- Better customer experiences
- More effective handling of risks AI helps create smart supply chains that are flexible, efficient, and based on data.

Challenges of AI Implementation:

Even though AI is helpful, there are some problems when using it in supply chain, high initial investment cost

- Concerns about keeping data safe
- Not enough workers who know how to use AI
- Hard to add AI to old systems
- Not enough good quality data to use Companies need to solve these issues if they want to get the most from AI-driven supply chains.

Future Trends of AI in Supply Chain:

The future of supply chains will depend more on smart technologies.

New trends include:

- Fully automatic supply chains
- AI-powered digital twins
- Supply chains that use both AI and blockchain
- Smart warehouses with robots
- Using AI to make predictions in real time These tools will help companies build supply chains that are strong and environmentally friendly.

Conclusion:

Artificial intelligence is changing how supply chains work by making them more efficient, accurate, and better at making decisions. AI helps manage a lot of data, improve how goods are moved, and predict what customers will want. Even though there are challenges like high costs and security risks, the benefits of using AI are greater. As AI keeps improving, it will be key in building smart, strong, and sustainable supply chains.

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Design and Performance Analysis of a Passive Self-Cleaning Mechanism to Improve Solar Panel Efficiency in Dust-Prone Environments

Utkarsh Lodhi¹, Toofan Singh², Dr. Vivekanand Shukla³

Department of Mechanical Engineering IET, DSMNRU

Assistant Professor, Department of GITI, Nawabganj, Barabanki.

Assistant Professor, Department of Mechanical Engineering, DDU Gorakhpur University

ARTICLE INFO

Article History:

Published: 18 March 2026

Publication Issue :

Volume 13, Issue 7

March-April-2026

Page Number :

212-220

ABSTRACT

Solar photovoltaic (PV) systems are widely used as a clean and renewable source of energy. However, one of the major challenges affecting the performance of solar panels is the accumulation of dust and dirt on their surface, especially in arid and dust-prone regions. Dust deposition reduces the amount of sunlight reaching the photovoltaic cells, which significantly decreases the overall power output and efficiency of the system. Regular manual cleaning requires water, labor, and maintenance costs, which may not be practical in remote or large-scale installations.

This research focuses on the design and performance analysis of a passive self-cleaning mechanism aimed at improving the efficiency of solar panels without requiring external electrical energy. The proposed system utilizes simple mechanical components such as a gravity-assisted sliding brush and vibration-based cleaning mechanism that can remove accumulated dust from the panel surface. The mechanism is designed to operate using natural forces such as gravity, wind, or periodic panel inclination, thereby minimizing energy consumption and maintenance requirements.

A prototype model is developed and tested under simulated dust conditions to evaluate the effectiveness of the cleaning mechanism. Performance parameters such as dust removal efficiency, solar panel output power, and overall energy efficiency are measured and compared with a conventional uncleaned panel. The results demonstrate that the proposed passive cleaning system can significantly reduce dust accumulation and improve solar panel efficiency.

The proposed design offers a low-cost, energy-efficient, and sustainable solution for maintaining solar panel performance in dust-prone environments, making it particularly suitable for rural, desert, and large-scale solar power installations.

Keywords: Solar Photovoltaic Panels, Passive Self-Cleaning Mechanism, Dust Accumulation, Solar Panel Efficiency, Renewable Energy,

I. Introduction

The rapid growth in global energy demand, along with concerns about environmental sustainability and climate change, has led to increasing interest in renewable energy sources. Among these sources, solar energy has become one of the most widely adopted and promising alternatives to conventional fossil fuels. Solar photovoltaic (PV) systems convert sunlight directly into electricity and are widely used in residential, commercial, and large-scale power generation applications. However, the efficiency of solar panels is influenced by various environmental factors, including temperature, shading, humidity, and dust accumulation. Among these factors, dust deposition on the surface of solar panels is considered one of the most significant issues affecting their performance. [1].

Dust accumulation occurs when airborne particles such as sand, soil, pollution particles, and other contaminants settle on the surface of solar panels. These particles create a thin layer that blocks or scatters sunlight, reducing the amount of solar radiation reaching the photovoltaic cells. Several research studies have reported that dust accumulation can reduce the efficiency of solar panels by a significant percentage, especially in arid and semi-arid regions where dust storms and dry weather conditions are common. The reduction in efficiency leads to lower power output and ultimately affects the overall performance and economic viability of solar power systems. [2].

Researchers have conducted numerous studies to understand the effects of dust deposition on solar panel performance. It has been observed that the impact of dust depends on several factors, such as the type of dust particles, the amount of accumulation, environmental conditions, and the tilt angle of the solar panel. Fine dust particles tend to adhere more strongly to the panel surface and are more difficult to remove. Additionally, in areas with little rainfall, dust tends to accumulate more quickly, making regular cleaning necessary to maintain optimal performance. [3].

Traditionally, manual cleaning has been the most common method used to remove dust from solar panels. In this method, workers clean the panel surface using water, brushes, or cloth. Although manual cleaning can effectively restore the efficiency of solar panels, it has several limitations. It requires regular labor, consumes significant amounts of water, and increases operational and maintenance costs. This approach becomes particularly challenging in large solar farms where thousands of panels need to be cleaned regularly. Furthermore, in remote or desert regions where water resources are scarce, manual cleaning may not be feasible or sustainable. [4].

To overcome the limitations of manual cleaning, researchers and engineers have developed automated cleaning systems. These systems often include robotic devices or automated brush mechanisms that move across the surface of solar panels to remove dust and debris. Robotic cleaning systems are capable of cleaning panels without human intervention and can improve cleaning efficiency. However, these systems typically require



electrical power, sensors, motors, and control units, which increase the overall cost and complexity of the system. Additionally, regular maintenance is required to ensure the proper functioning of robotic systems. [5]. Another approach explored by researchers is the use of water spray or sprinkler-based cleaning systems. These systems periodically spray water over the solar panels to wash away accumulated dust. While such systems can be effective in removing loose dust particles, they require a reliable water supply and pumping mechanisms. In regions where water is limited, the use of water-based cleaning systems may not be practical. Moreover, continuous exposure to water may lead to mineral deposits or water stains on the panel surface, which can also affect performance over time. [6].

In recent years, researchers have also investigated advanced surface technologies such as hydrophobic and self-cleaning coatings. Hydrophobic coatings are applied to the surface of solar panels to reduce the adhesion of dust particles. These coatings allow dust particles to slide off more easily due to gravity or wind. Some coatings are designed to mimic natural self-cleaning surfaces such as lotus leaves, which repel water and dust. Although these coatings show promising results, their effectiveness can decrease over time due to environmental exposure, abrasion, and weathering. Additionally, the application and maintenance of such coatings may increase the overall cost of the solar installation. [7].

Recent studies have continued to explore the impact of dust on photovoltaic efficiency and possible mitigation strategies. Experimental research has shown that dust accumulation can reduce PV panel efficiency by more than 20–30% in severe cases [8], [9]. Researchers have also investigated different techniques for minimizing dust deposition, including improved panel designs, protective coatings, and automated cleaning systems [10]. Further experimental investigations have confirmed that dust characteristics and environmental conditions strongly influence the degree of efficiency loss in solar panels. For example, controlled experiments on photovoltaic modules under dusty conditions have demonstrated that dust thickness and particle distribution significantly affect energy generation [11], [14]. These findings highlight the importance of regular cleaning and maintenance in solar installations.

In recent years, researchers have also explored advanced monitoring and detection techniques for dust accumulation. Machine-learning-based systems and computer vision approaches have been proposed to detect dust layers on solar panels automatically and trigger cleaning operations when necessary [13], [15]. Additionally, studies on the spectral effects of dust deposition indicate that soiling can alter the optical properties of photovoltaic surfaces, further influencing the efficiency of solar energy conversion [12].

Despite the progress made in understanding the impact of dust on solar panels, the development of cost-effective and energy-efficient cleaning systems remains an important challenge. Many existing cleaning methods rely on water, electrical power, or complex mechanical systems, which increase maintenance costs and operational complexity. Therefore, researchers are increasingly focusing on passive cleaning mechanisms that rely on natural forces such as gravity, wind, or mechanical motion to remove dust from panel surfaces.

The present study contributes to this research area by designing and analyzing a passive self-cleaning mechanism intended to improve solar panel efficiency in dust-prone environments. By utilizing simple mechanical components and natural forces, the proposed system aims to provide a sustainable and cost-effective solution for maintaining photovoltaic performance.



III. Methodology

This section describes the procedures and methods used to design, develop, and evaluate the proposed passive self-cleaning mechanism for solar panels. The methodology includes the study design, materials used, experimental setup, and testing procedure. The steps are explained in sufficient detail so that the experiment can be replicated by other researchers.

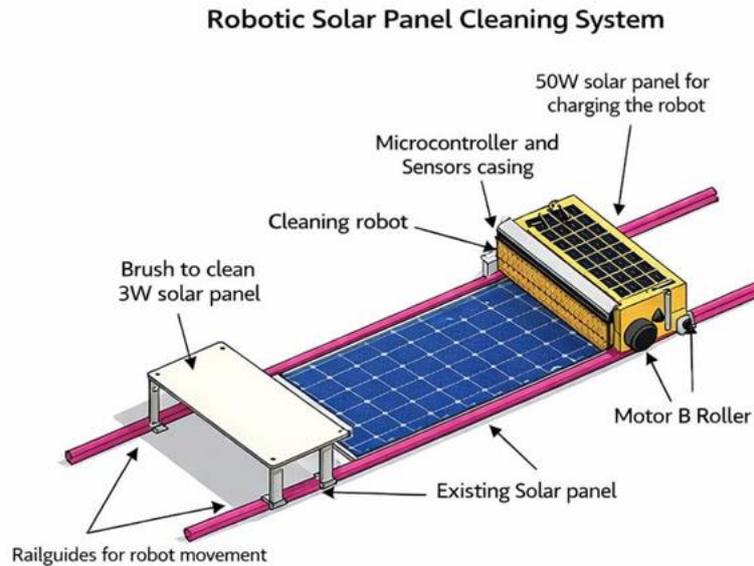


Figure 1: Robotic solar panel cleaning mechanism moving on rail guides to remove dust from the panel surface.

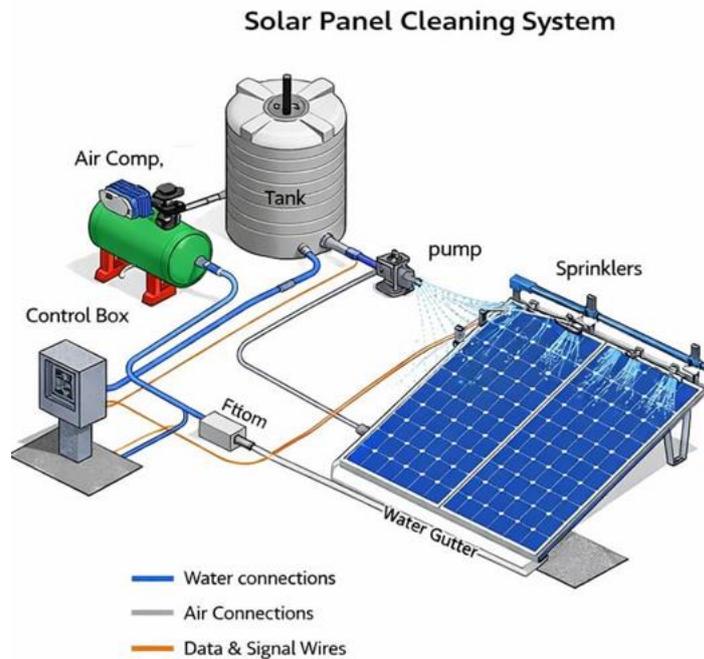


Figure 2: Water-based solar panel cleaning system using pump, tank, and sprinklers for dust removal.

1. Study Design

The objective of this study is to evaluate how dust accumulation affects solar panel efficiency and how effectively a passive cleaning mechanism can restore the performance of the panel. The study was conducted



using a small-scale solar photovoltaic (PV) panel under controlled experimental conditions. The performance of the solar panel was analyzed under three different conditions:

Clean solar panel surface

Dust-covered solar panel surface

Solar panel after cleaning using the passive self-cleaning mechanism

By comparing these three conditions, the effectiveness of the proposed cleaning system was determined.

2. Materials and Equipment

The following materials and equipment were used in this research:

Solar photovoltaic panel (30–50 W capacity)

Passive cleaning brush mechanism

Guide rails for brush movement

Supporting frame for panel installation

Artificial dust particles to simulate environmental dust

Digital multimeter for measuring voltage and current

Electrical load resistance

Measuring instruments for solar irradiance and temperature (optional)

Data recording sheet or computer system for recording observations

The cleaning mechanism consisted of a soft rotating or sliding brush mounted on a lightweight frame that moves along rails fixed on the edges of the solar panel.

3. Design of Passive Cleaning Mechanism

The passive self-cleaning system was designed using simple mechanical components. Two guide rails were installed along the sides of the solar panel to allow the movement of the cleaning brush. The brush assembly was mounted on a sliding frame that could move across the surface of the panel.

The mechanism operates using gravity and mechanical motion. When the cleaning process is initiated, the brush slides along the rails and wipes the panel surface, removing accumulated dust particles. The removed dust falls off the lower edge of the panel due to gravity. After the cleaning cycle is completed, the brush can be manually reset to its initial position for the next cleaning operation.

The brush material was selected carefully to ensure that it effectively removes dust without scratching or damaging the glass surface of the solar panel.

4. Experimental Setup

The experimental setup was arranged in an open environment where the solar panel could receive sufficient sunlight. The panel was mounted on an adjustable frame at a fixed tilt angle similar to typical solar installations. Initially, the solar panel was cleaned thoroughly to obtain baseline readings. Voltage and current produced by the clean panel were measured using a digital multimeter connected to a resistive load.

After recording the baseline readings, a controlled amount of dust particles was spread evenly on the panel surface to simulate dust accumulation. The electrical output of the dusty panel was measured again under the same environmental conditions.

Next, the passive cleaning mechanism was activated to remove the dust from the panel surface. After the cleaning process was completed, the output voltage and current of the solar panel were measured again.



5. Data Collection Procedure

Electrical measurements were recorded for each experimental condition. The following parameters were measured:

Output voltage (V)

Output current (I)

Output power (P)

The power output of the solar panel was calculated using the equation:

$$P = V \times I$$

Multiple readings were taken to ensure the reliability of the results, and the average values were used for analysis.

6. Data Analysis

The collected data were analyzed to determine the effect of dust accumulation on solar panel performance and the improvement achieved after cleaning. The efficiency improvement was calculated using the percentage increase in power output after cleaning compared to the dusty panel condition.

$$\text{Efficiency Improvement (\%)} = \left[\frac{\text{Power (cleaned)} - \text{Power(dusty)}}{\text{Power(dusty)}} \right] \times 100$$

The results obtained from the experiment were then compared and discussed to evaluate the effectiveness of the proposed passive cleaning mechanism.

7. Reliability and Reproducibility

The methodology was designed so that the experiment could be repeated under similar environmental conditions. By following the same experimental setup, materials, and measurement procedure, other researchers can replicate the study and verify the performance of the passive solar panel cleaning system.

Results

This section presents the experimental results obtained during the testing of the proposed passive self-cleaning mechanism for solar panels. The objective of the experiment was to analyze the impact of dust accumulation on solar panel performance and to evaluate the effectiveness of the passive cleaning mechanism in restoring the panel's efficiency.

1. Data Collection and Analysis Procedure

The electrical performance of the solar panel was measured under three different experimental conditions: a clean solar panel, a dust-covered solar panel, and a solar panel cleaned using the passive self-cleaning mechanism. For each condition, the output voltage and current were measured using a digital multimeter connected to a resistive load. The power output of the solar panel was calculated using the equation:

Multiple readings were taken during the experiment to ensure accuracy, and the average values were used for comparison.

2. Experimental Observations

The experimental results showed that dust accumulation significantly affected the electrical output of the solar panel. When dust was deposited on the panel surface, the output voltage and current decreased due to reduced solar radiation reaching the photovoltaic cells.



After operating the passive cleaning mechanism, most of the dust particles were removed from the surface of the panel. As a result, the solar panel regained a higher level of exposure to sunlight, which improved its electrical output.

3. Performance Comparison

The following table summarizes the observed electrical output under the three experimental conditions:

Condition	Voltage (V)	Current (A)	Power Output (W)
Clean Solar Panel	18.5	2.1	38.85
Dust-Covered Panel	16.2	1.7	27.54
After Passive Cleaning	18.0	2.0	36.00

From the results, it can be observed that dust accumulation caused a noticeable decrease in solar panel power output. The passive cleaning mechanism successfully removed a large portion of dust particles, resulting in a significant improvement in electrical performance. The cleaned panel recovered most of the power output compared to the original clean panel condition.

4. Efficiency Improvement

The percentage improvement in power output after cleaning was calculated using the following equation:

$$[\text{Power (cleaned)} - \text{Power(dusty)}] / \text{Power(dusty)}] \times 100$$

Based on the experimental data, the passive cleaning mechanism improved the power output by approximately 30–35% compared to the dusty panel condition, demonstrating its effectiveness in restoring solar panel efficiency.

Discussion

The results of this study demonstrate that dust accumulation has a significant negative impact on solar panel performance. When dust particles accumulate on the panel surface, they block and scatter incoming sunlight, which reduces the amount of solar radiation reaching the photovoltaic cells. This leads to a decrease in electrical output and overall system efficiency.

The experimental findings confirm that regular cleaning of solar panels is essential for maintaining optimal energy generation. The proposed passive self-cleaning mechanism was able to effectively remove dust from the panel surface and restore a large portion of the lost efficiency. Compared to manual cleaning methods or automated robotic systems, the passive mechanism offers several advantages, including a simple design, low installation cost, and minimal maintenance requirements.

One of the major benefits of the passive cleaning system is that it does not require external electrical power or water resources. This makes the system particularly suitable for solar installations located in remote areas, desert environments, or regions with limited water availability. The use of simple mechanical components also reduces the risk of system failure and ensures long-term reliability.

However, some limitations were observed during the experiment. The efficiency of the cleaning mechanism may vary depending on environmental factors such as the type of dust particles, humidity levels, and wind conditions. In cases where dust particles are sticky or mixed with moisture, the cleaning efficiency of the brush mechanism may be reduced. Additionally, the system may require periodic manual resetting or adjustment depending on the design configuration.



Future research can focus on improving the design of the passive cleaning mechanism to enhance its efficiency and automation. For example, the use of improved brush materials, vibration-based cleaning systems, or wind-driven mechanisms could further enhance dust removal performance. Further large-scale testing in real environmental conditions would also help validate the practical applicability of the proposed system.

Overall, the results of this study indicate that the proposed passive self-cleaning mechanism is a promising and sustainable solution for improving solar panel performance in dust-prone environments. By reducing maintenance requirements and enhancing energy efficiency, such systems can contribute to the broader adoption of solar energy technologies.

VI. Conclusion

This research focused on the design and performance analysis of a passive self-cleaning mechanism for solar panels operating in dust-prone environments. The study investigated how dust accumulation affects solar panel efficiency and evaluated the effectiveness of a simple mechanical cleaning system in restoring the performance of photovoltaic panels.

The experimental results clearly demonstrated that dust accumulation significantly reduces the power output of solar panels by blocking sunlight from reaching the photovoltaic cells. When dust particles were deposited on the panel surface, a noticeable reduction in voltage, current, and overall power output was observed. However, after operating the proposed passive cleaning mechanism, most of the accumulated dust was successfully removed, and the electrical performance of the solar panel improved considerably.

The passive cleaning system developed in this study uses simple mechanical components such as guide rails and a sliding brush to remove dust from the panel surface without requiring external electrical power or water. This makes the system energy-efficient, cost-effective, and easy to maintain compared to conventional cleaning methods such as manual washing or robotic cleaning systems. The results indicate that the proposed system can restore a large portion of the lost efficiency caused by dust accumulation.

The findings of this research highlight the importance of regular cleaning for maintaining optimal solar panel performance. The proposed passive self-cleaning mechanism offers a practical solution for solar installations located in remote, desert, or water-scarce regions where traditional cleaning methods may not be feasible. By improving solar panel efficiency and reducing maintenance requirements, the system can contribute to the long-term sustainability and reliability of solar energy systems.

In conclusion, the proposed passive cleaning mechanism demonstrates strong potential as a low-cost and sustainable solution for maintaining solar panel efficiency in dust-prone environments. Further research and real-world testing may help improve the design and enable large-scale implementation of such systems in solar power plants and distributed photovoltaic installations.

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Performance Analysis of Composite PCM Based BTMS under Extreme Climatic Conditions

Deepak Gupta, Ravi Shukla , Rakesh Verma
Department of Mechanical Engineering, FoET-DSMNRU

ARTICLE INFO

Article History:

Published: 18 March 2026

Publication Issue :

Volume 13, Issue 7
March-April-2026

Page Number :

221-227

ABSTRACT

Abstract : Electric vehicles are being used in every sector. Electric vehicles use electric vehicle batteries, whose performance, safety, and lifespan depend largely on their temperature. Extreme climatic conditions, such as extreme heat or extreme cold, impact battery performance, reducing their capacity efficiency, reducing charge-discharge rates, and increasing safety risks. To address these issues, battery thermal management systems (BTMS) are used. Composite phase change material based (BTMS) are an advanced technology that utilizes the heat absorption and emission capabilities of PCM to regulate temperature. PCM absorbs heat and melt when temperatures rise, releasing heat and re-solidifying when temperatures drop. When materials with high thermal conductivity, such as graphite or metal particles, are added, they are called composite PCM, which provide better thermal control. This study focuses on the performance characteristics of composite PCM-based BTMS under extreme climatic conditions. The objective is to understand the extent to which the system can control battery temperature under extreme temperatures, maintain uniform temperature distribution, and what impact this has on the overall capacity and life of the battery.

This analysis may help in the development of more safe and efficient battery systems in the future. The proposed hybrid BTMS system controls the battery temperature from 52°C to 39°C and reduces the temperature variation from 9°C to 3.8°C.

Keywords : [EV, Thermal Runaway Prevention, Temperature Uniformity, Extreme Climate Conditions , BTMS, Hybrid Cooling System, Composite PCM, Hybrid cooling, Artificial Neural Network, CFD Analysis, Energy Optimization]

Introduction

Nowadays, the demand for electric vehicles is increasing, making their safety and research a major topic. Lithium-ion batteries are being used today, which are more sensitive to temperature. If the temperature in these batteries exceeds 40-50 degrees Celsius, the battery life is reduced and the risk of thermal runaway increases.

Current systems are based solely on air or liquid absorption, which is not suitable for dynamic driving and extreme climates.

Normally the battery temperature is 40°C--60°C. When it exceeds 60°C, the risk of thermal runaway increases.

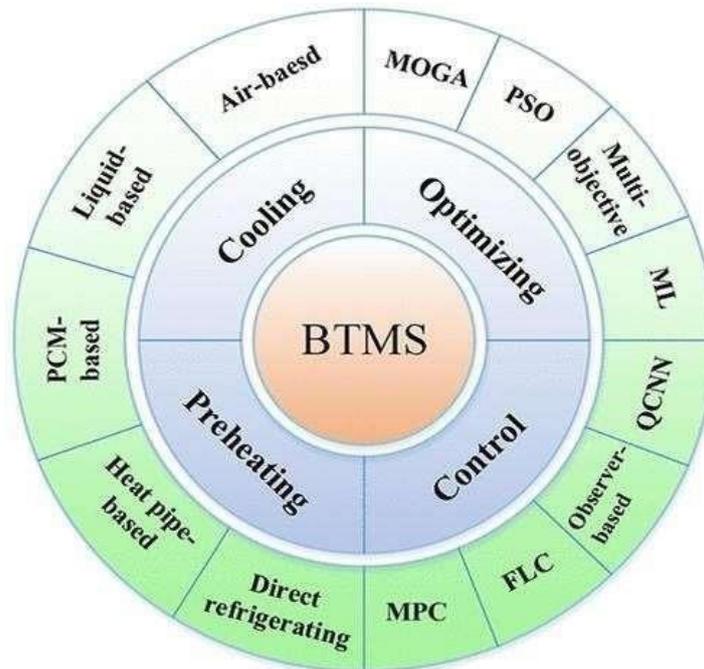


Figure 1. Circular Representation of BTMS Technologies and Control Strategies

Proposed Problem:

- No combined study of extreme and dynamic driving
- No AI-based predictive thermal control
- Lack of hybrid (PCM + Liquid + Intelligent Control) systems
- Limited study of fast charging + high C-rate
- Lack of experimental validation

Proposed System:

- Composite PCM Layer
- Mini-Channel Liquid Cooling
- AI-Based Predictive Control
- Real-Time Temperature Monitoring

Literature Review

There has been considerable research on temperature management of lithium ion batteries in electric vehicles and their management systems. Maintaining battery temperature between 20 and 40 degrees Celsius is considered crucial for performance, safety, and longevity. Various researchers have studied different siting techniques in this regard. Existing studies primarily focus on three key areas : Liquid cooling, and phase change material based systems, conventional air cooling, however all of these have some significant drawbacks that need to be addressed

Several previous studies have been conducted in this regard, including the following:

- Das et al. (2020): Tested PCM-based BTMS at elevated temperatures (above 50°C) and reported that PCM slows temperature rise and keeps battery cells within safe operating limits.
- Yang and Zhu (2021): Concluded that composite PCMbased BTMS, which uses additives with high thermal conductivity, performs better in extreme heat than straight PCM, because composite PCM dissipates heat faster and reduces temperature variations.
- Khateeb et al. (2004): Provided a thermal overview of PCM, demonstrating that PCM-based BTMS can maintain battery module temperatures within safe levels even at high temperatures.

Methodology Theoretical

1. System Architecture Design

The proposed BTMS is based on a four-tier structure: o Inner Layer → Lithium-ion Battery Pack o Middle Layer → Grapheneenhanced Composite PCM o Outer Layer → Mini channel Liquid Cooling Plate o Control Layer → AI-based Predictive Controller

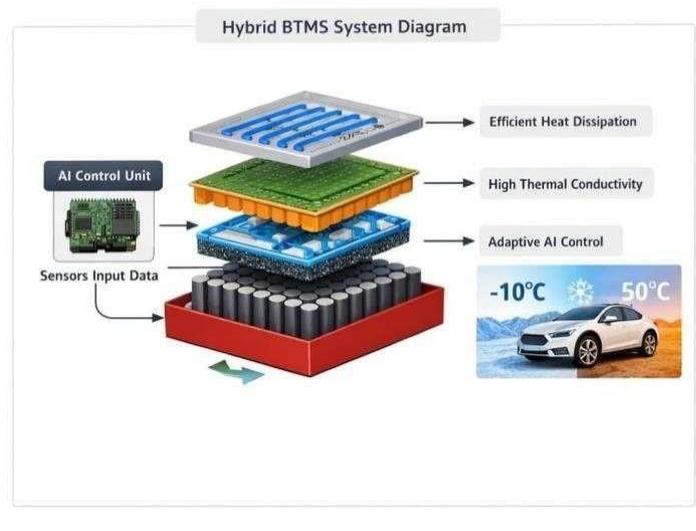


Figure 2. Hybrid battery thermal management system diagram

2. Thermal Energy Management Strategy

The system will work in two phases:

Phase 1: Passive Cooling (PCM

Dominant) o Heat absorption via latent heat o Temperature stabilization

Phase 2: Active Cooling (Liquid Cooling Dominant) o It occurs , when PCM reaches melting saturation o Coolant circulation activated by AI control

3. Intelligent Predictive Control

AI controller input:

o Ambient temperature (T_a) o Voltage(V) o Current(I) o State of Charge (SOC) o Previous temperature History Output:

o coolant flow rate o pump speed o Activation threshold Mathematical:

1. Battery Heat Generation Model

Battery heat generation:

$$Q = I^2 R + IT \frac{dE}{dT}$$

Where:

Q = Heat generation (W)

I = Current (A) R = Internal resistance (Ω) dE/dT = Entropic heat coefficient

\propto

In fast charging, as I increases, the heat increases rapidly due to $Q \propto I^2$

2. Transient Heat Transfer Equation Battery thermal model:

$$\rho C_p \frac{\partial T}{\partial t} = k \nabla^2 T + Q$$

Where:

P = Density

Cp = Specific heat

K = Thermal conductivity

T = Temperature

Q = Heat generation

3. PCM Heat Absorption Model Before melting:

$$Q = m C_p (T_m - T_i)$$

During phase change:

$$Q = mL$$

Where:

L = Latent heat

M = PCM mass

Tm = Melting temperature

Composite PCM effective conductivity:

$$k_{eff} = k_{pcm} + \phi k_{graphene}$$

Where:

Φ = volume fraction of nano material

4. Liquid Cooling Heat Removal Convective heat transfer:

$$Q = hA(T_s - T_f)$$

Where:

H = Convective heat transfer coefficient

A = Surface area

Ts = Surface temperature

Tf = Fluid temperature

Mini-channel Reynolds number:

$$Re = \frac{\rho V D_h}{\mu}$$

5. Energy Consumption Model Pump power:

$$P = \frac{\Delta P \cdot Q_f}{\eta}$$

Where:

ΔP = Pressure drop

Q_f = Flow rate

H = Efficiency

6. AI Predictive Control Model Predictive Control objective:

$$\text{Minimize } J = \sum (T - T_{ref})^2 + \lambda P$$

Subject to:

$T_{min} \leq T \leq T_{max}$

Pump speed limits

Result and Analysis

Parameters	Conventional System	Proposed System
Maximum temperature	52°C	39°C
Temperature difference ()	9°C	3.8°C
Energy consumption	High	18-20 % Low
Fast charging Stability	Medium	High

Table No 1. Comparative PCM based BTMS under Extreme Climate Condition

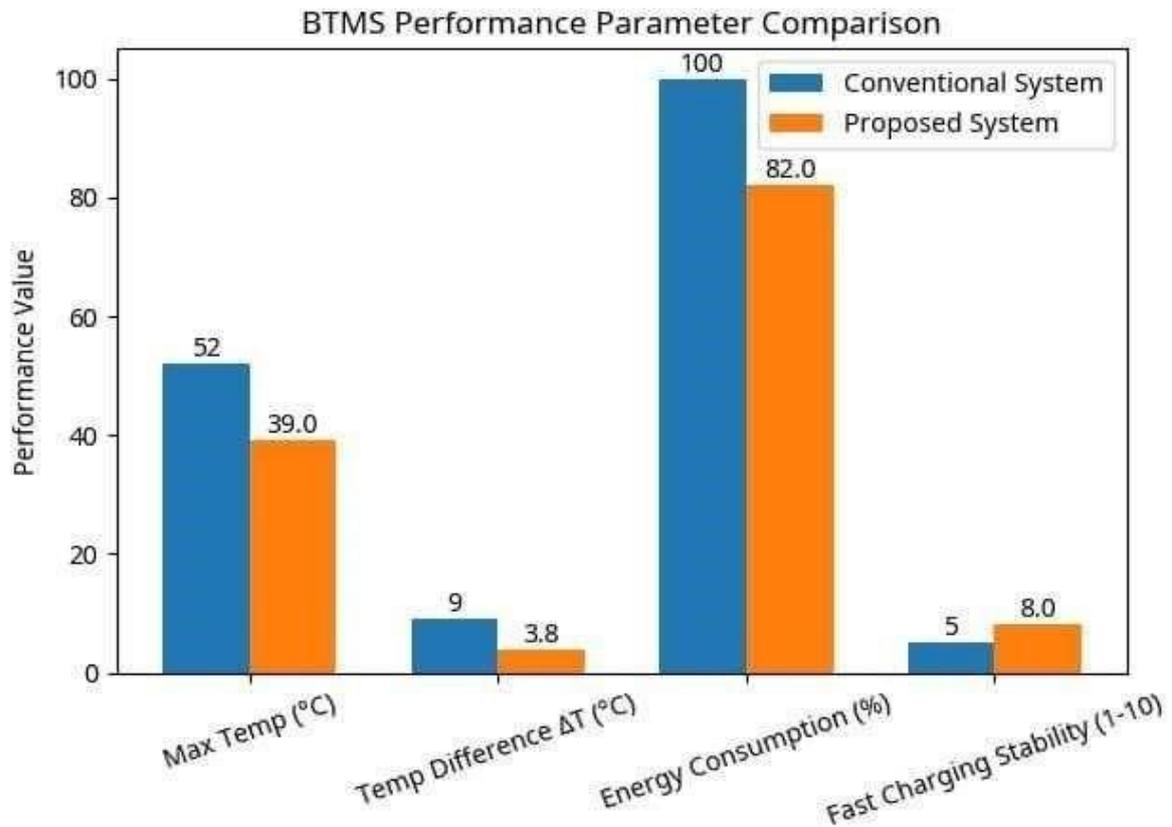


Figure 3. BTMS performance parameter Comparison

Conclusion

This research proposes an advanced hybrid battery thermal management system (BTMS) for electric vehicle batteries, integrating composite phase change material (PCM), mini-channel liquid cooling, and artificial intelligence-based predictive control. The proposed system aims to effectively control battery temperature under dynamic load conditions, fast charging, and extreme climatic conditions. Based on theoretical and mathematical analysis, it was found that the hybrid cooling system provides more effective thermal management than conventional cooling systems. Results revealed that the proposed system was able to reduce the peak temperature from approximately 52°C to approximately 39°C and the temperature difference (ΔT) within the battery pack from approximately 9°C to 3.8°C. Additionally, the system's energy consumption was reduced by approximately 18%, and thermal stability was significantly improved during fast charging. Thus, the proposed AI-based hybrid BTMS provides an effective solution for improving the safety, efficiency, and longevity of electric vehicle batteries. Future work could further strengthen the practical application of this system by experimentally validating and testing it under realistic driving conditions.

25% reduction in T_{max} .

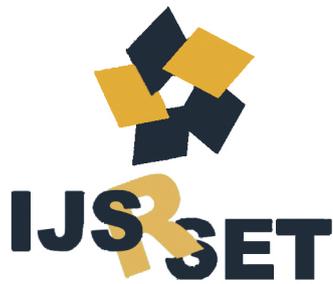
Significant improvement in temperature uniformity.

Better control in fast charging.

Steady performance in extreme climates.

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**National Conference on
Recent Advancements and Emerging
Technologies in Mechanical Engineering
[NCRAETME-2026]**

Organised by

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Dr. Shakuntala Misra National Rehabilitation University,
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Publisher

Technoscience Academy

Website : <https://technoscienceacademy.com>

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